ARPA-E Fusion-Energy Programs and Plans

Presentation to FESAC
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High-level ARPA-E perspective

- Fusion strategic plan should be responsive to dynamic constraints imposed by evolving energy markets through an adequately diverse portfolio
  - Very different energy landscape shaped today’s fusion program
  - The competition today: LCOE <6 ¢/kWh, unit size <<1 GWe, capital cost <$1B, <$2/W
  - Fusion should absorb fission’s lessons (i.e., reduced capex and opex)

- Increased alignment between federal and private efforts could enhance fusion’s near-term relevance and raise the tide for all boats
  - Private fusion investments represent significant market pull
  - Little federal support today in specific areas of interest to private companies
  - Federal leadership-class capabilities will help accelerate private efforts
  - Difficult for federal or private efforts alone to achieve timely, commercially viable DEMO

- ARPA-E stands ready to coordinate further with FES; we can contribute strongly to
  - Developing impactful fusion public-private partnerships
  - Providing a detailed understanding of energy markets and commercialization requirements
  - Making connections to other energy researchers solving synergistic problems

Outline

- Introduction
- Brief review of the ALPHA* program (2015–2019)
- Fusion program plans (2019–?)
- Q&A (lots of backup materials)

*Accelerating Low-Cost Plasma Heating and Assembly

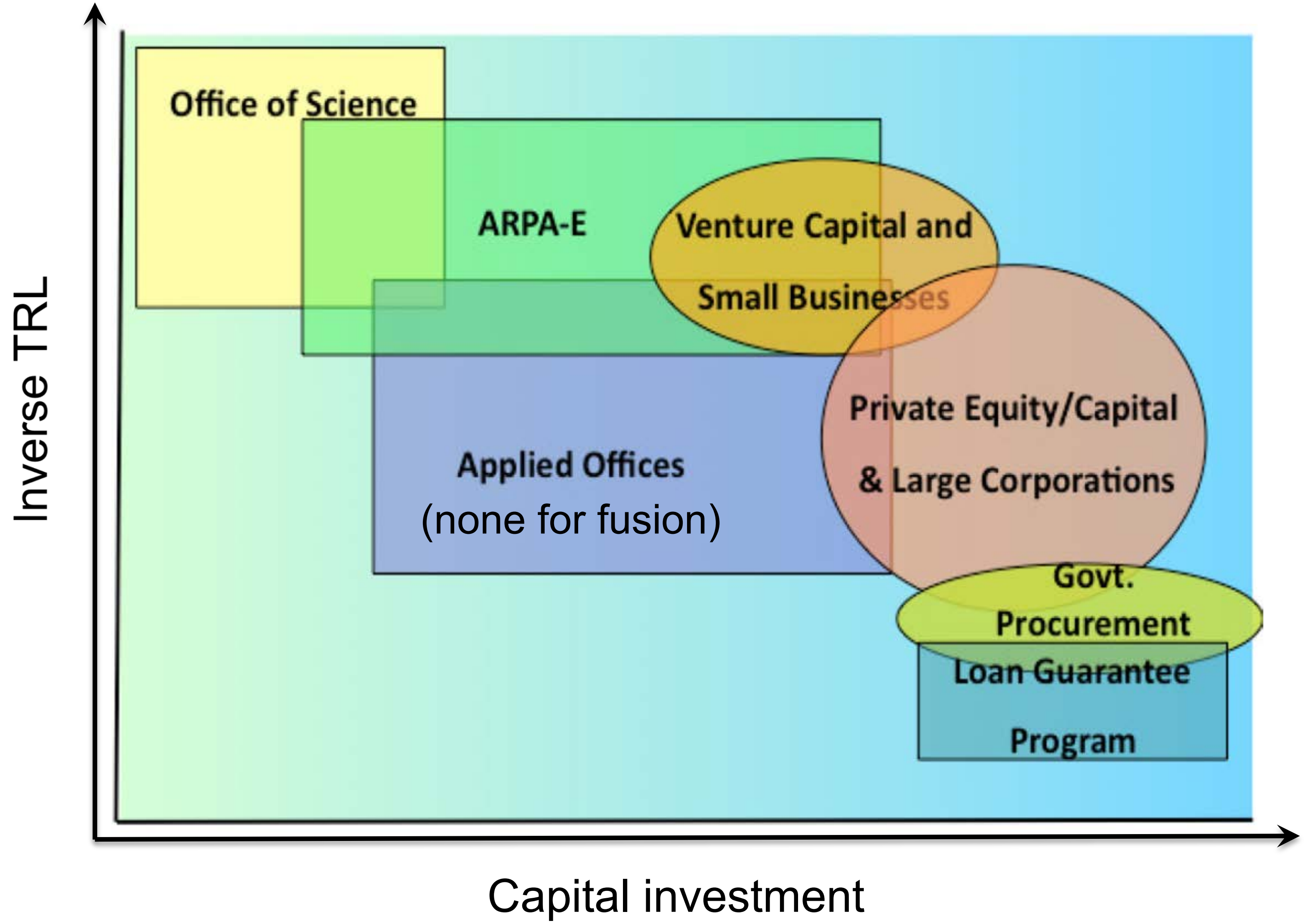
ARPA-E is an agency within the U.S. Dept. of Energy modeled after DARPA

Mission: To overcome long-term, high-risk technological barriers in energy-technology development by providing applied R&D funding for high-risk, high-reward transformational ideas

FY19 Enacted: $366M
FY20 House: $425M
FY20 Senate: $428M

National Academies report *An Assessment of ARPA-E* (2017)

ARPA-E supports transformative applied energy R&D, bridging the gap between basic research and energy commercialization



Adapted from former ARPA-E director A. Majumdar's House Science testimony, 2010

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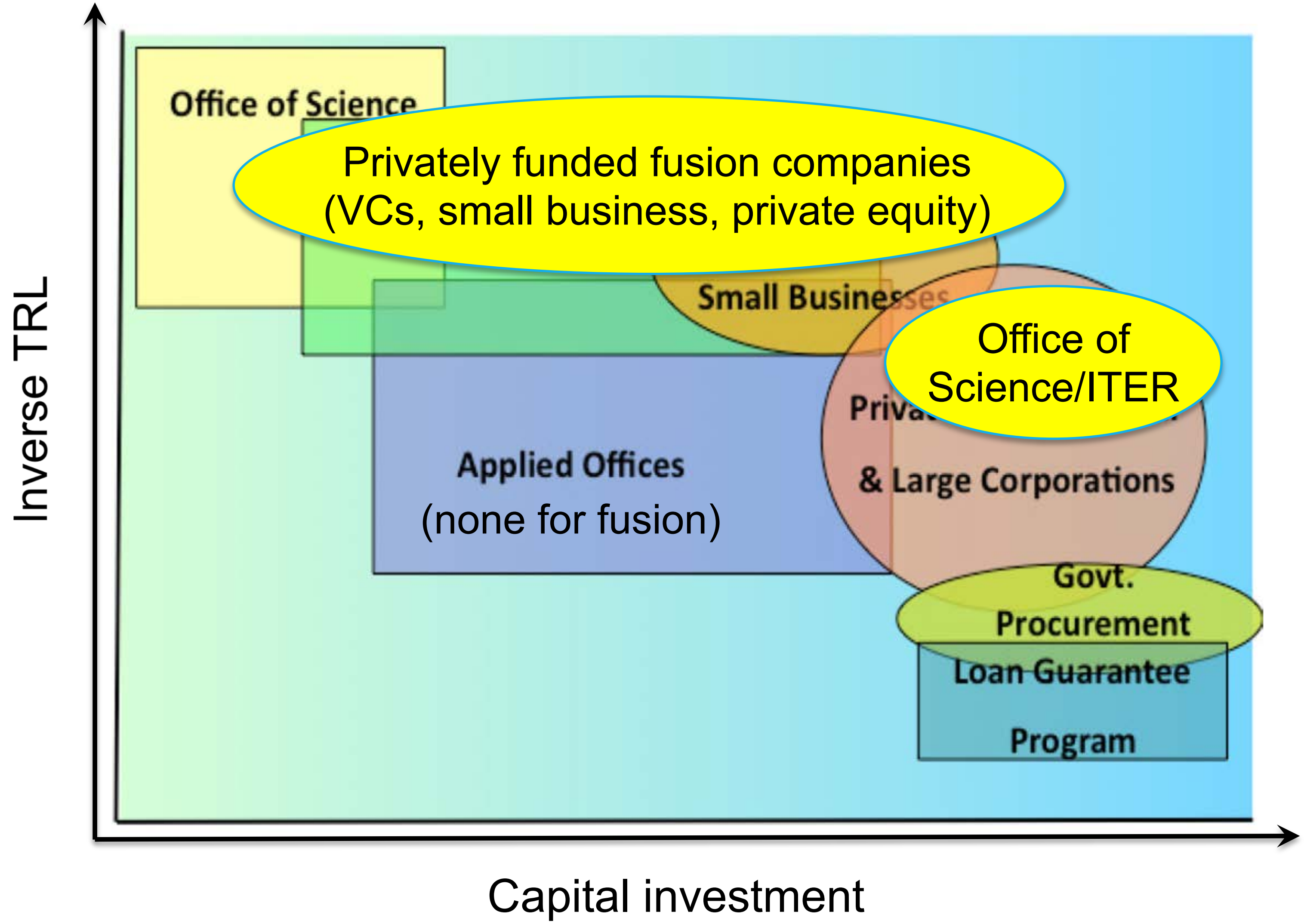
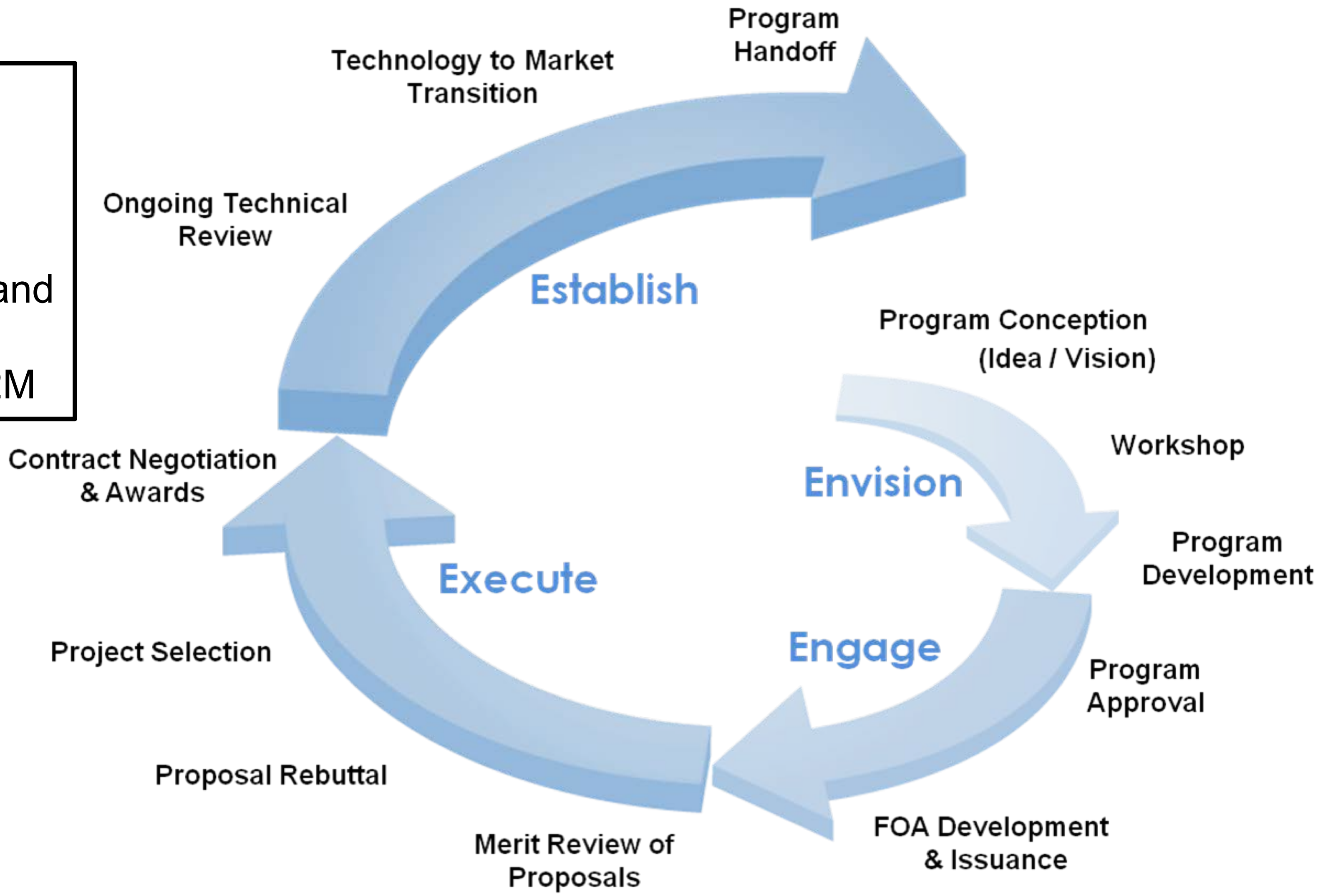


Adapted from former ARPA-E director A. Majumdar's House Science testimony, 2010

ARPA-E program development and execution process

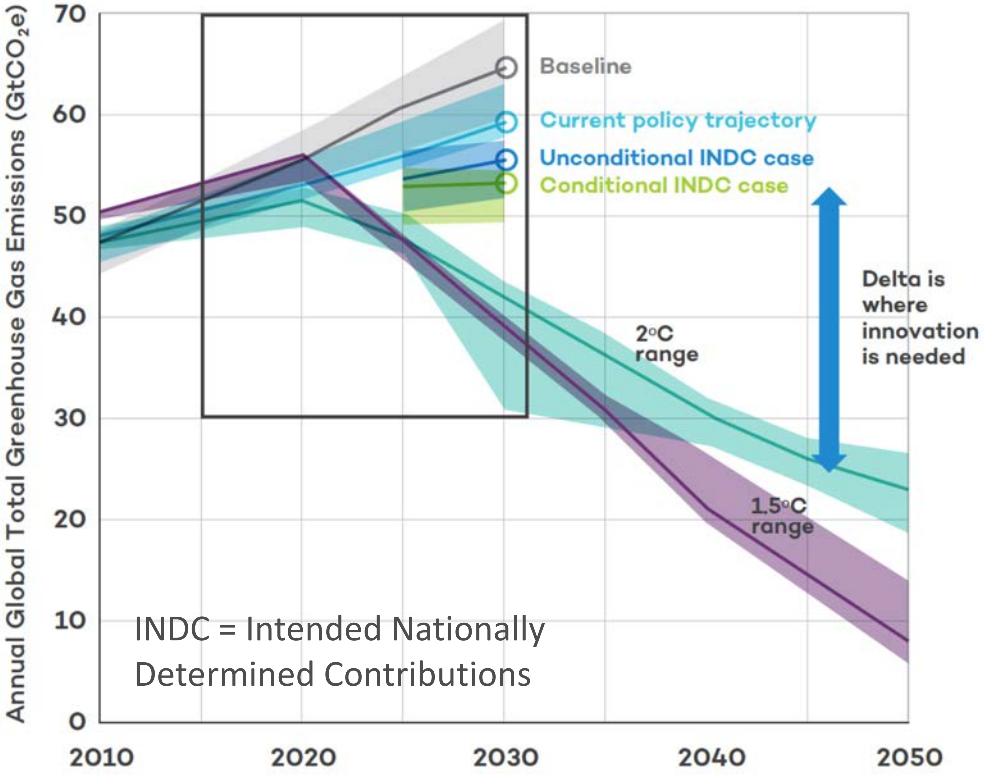
- Collaborative milestone negotiation
- Active project management and feedback
- Attention to T2M



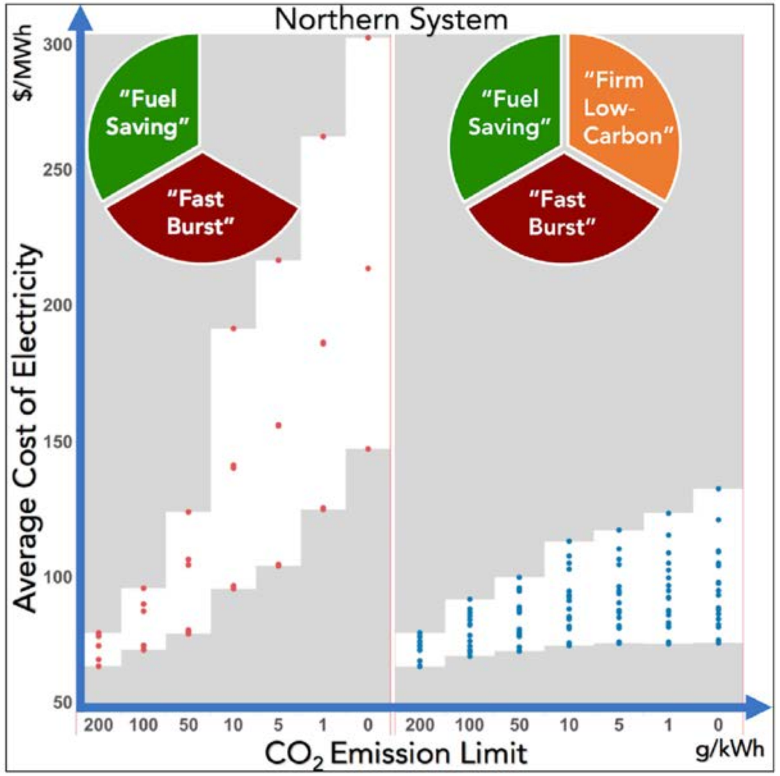
- Situational awareness
- Identification of “white space”
- Stakeholder engagement

What problem is fusion trying to solve? Risk mitigation for achieving a cost-effective zero-carbon grid by mid/late century

- Significant gap exists to achieve zero or negative carbon emissions by mid/late century
- Firm, low-carbon sources needed to keep costs reasonable



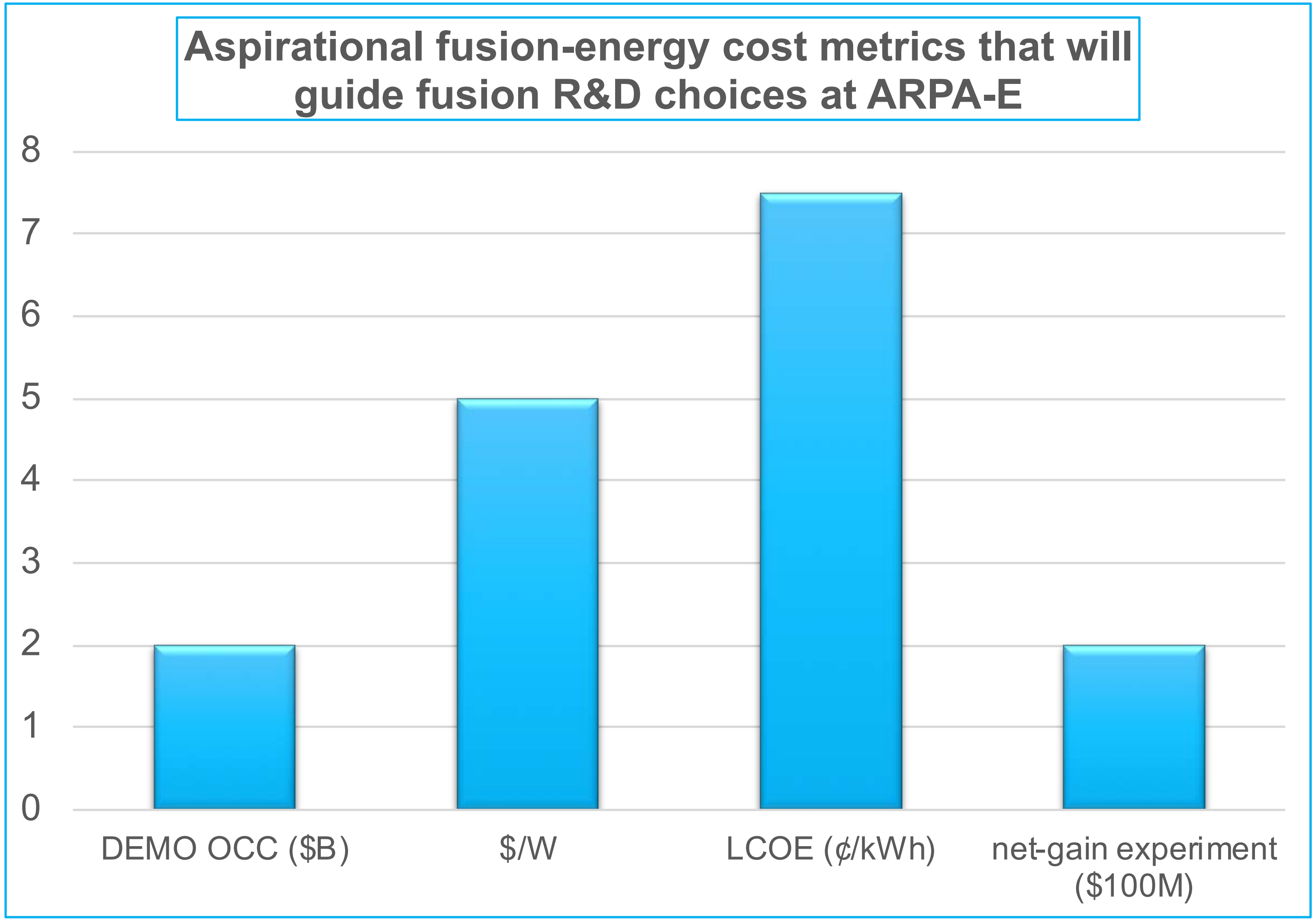
Energy Futures Initiative, 2018 (modified from UNEP Emissions Gap Report, 2017).



N. A. Sepulveda et al., Joule **2**, 2403 (2018)

See "Heilmeier questions," which must be answered in ARPA-E program formulation.

How much does fusion need to cost? We don't know for sure but have an idea based on competition and financing



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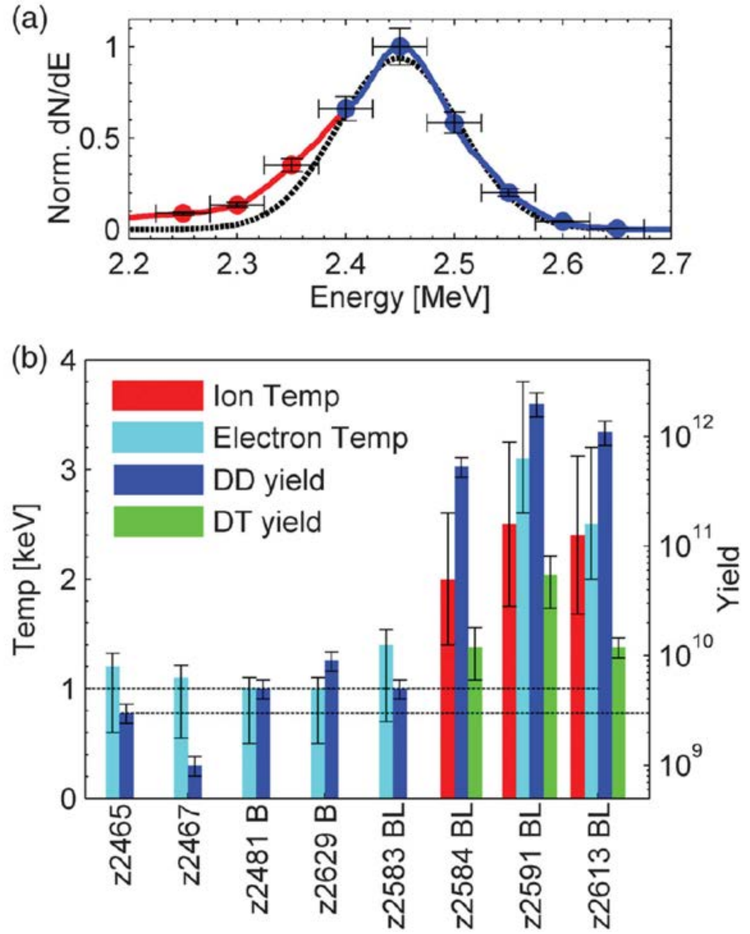
ALPHA program objectives ($30M over 3–4 years)

- Explore lower-cost path to fusion-energy development and eventual deployment
- Focus on pulsed approaches with final density of 10^{18}–10^{23} cm^{-3}
  - Magneto-inertial fusion (MIF) and Z-pinch variants
- Enable rapid learning
  - High shot rate: hundreds of shots during ALPHA, scalable to ≥1 Hz in a future power plant
  - Low cost per shot: "drivers" < $0.05/MJ and "targets" < 0.05 ¢/MJ over life of plant

Sandia MagLIF provided convincing MIF proof of concept → helped justify the program



See archived ALPHA program description and review paper, C. L. Nehl et al., "Retrospective of the ARPA-E ALPHA fusion program," J. Fusion Energy, accepted (2019).

M. R. Gomez et al., PRL **113**, 155003 (2014)
P. Schmit et al., PRL **113**, 155004 (2014)

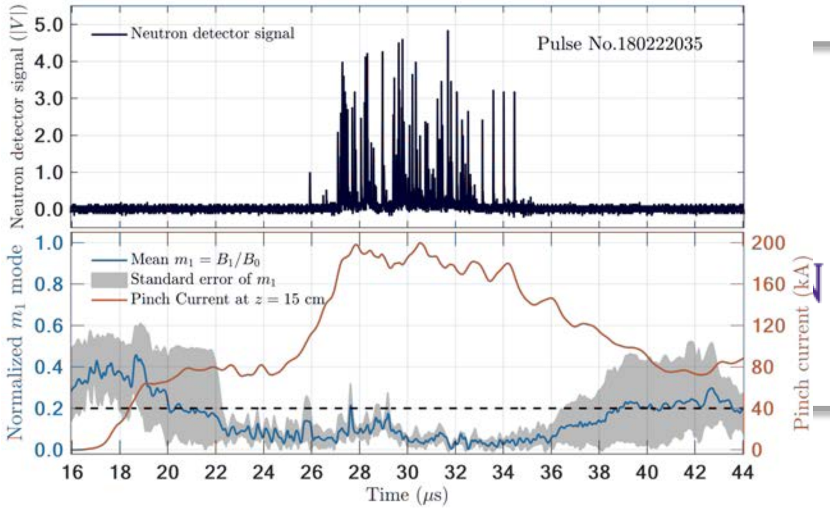
ALPHA portfolio (awards ~$400k–$5.9M)

Integrated concepts		Driver development		Applied MIF science	
Magnetic compression of an FRC	Helion Energy	Plasma guns to form high-speed plasma liners	Los Alamos National Laboratory	Underlying science of MIF at fusion conditions	Sandia National Laboratories
Shear-flow-stabilized Z-pinch (direct pulsed power)	University of Washington	Scalable MEMS-based ion accelerator	Berkeley Lab (Lawrence Berkeley National Laboratory)	Helical Taylor state as stable plasma target	Swarthmore
Staged Z-pinch (direct pulsed power)	MIFTI Clean Energy	Piston-driven liquid liner	NumerEx	Physics of plasma compression	California Institute of Technology

ALPHA portfolio (awards ~$400k–$5.9M)

Integrated concepts

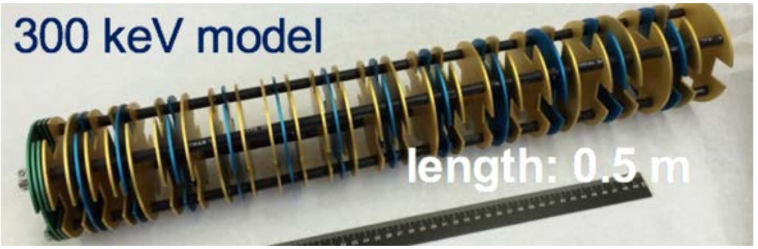
Magnetic compression of an FRC — Helion Energy



Staged Z-pinch (direct pulsed power) — MIFTI Clean Energy

Driver development

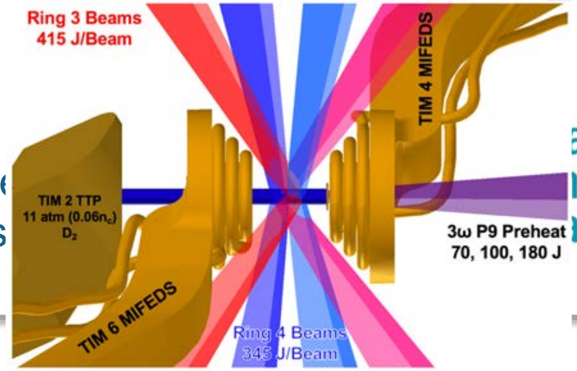
Plasma guns to form high-speed plasma liners — Los Alamos National Laboratory



Piston-driven liquid liner — NumerEx

Applied MIF science

scie
fus



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Helical Taylor state as stable plasma target — Swarthmore

Physics of plasma compression — California Institute of Technology

Summary of ALPHA outcomes

- Technical outcomes
  - Evidence of >1-keV temperatures and DD neutron production for 3 integrated concepts
  - Demonstrated two new, potential compression-driver technologies
  - Developed three new, low-cost, high-shot-rate platforms to study MIF target physics
- Tech-2-market (T2M) outcomes
  - 3 new spinoff companies and $35M private capital raised by ALPHA projects*
  - Dozens of peer-reviewed publications, 6 patent applications filed, APS-DPP mini-conference (2018)
  - ALPHA teams among the founding members of the Fusion Industry Association
- Positive (but cautious) findings from 2018 JASON report:
  - MIF within 10% of scientific breakeven for ~1% of total US fusion R&D funding
  - Near-term priority should be scientific breakeven in a system that scales to commercial power plant
  - Support all promising approaches; do not concentrate resources on early frontrunners

*Since 2015, publicly disclosed private funding into worldwide fusion R&D doubled to over $1.5B.

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ARPA-E interested in transformative fusion R&D to help enable grid-ready fusion demo in ~20 years for OCC* < "few $B"

Cost constraint

↓

Develop credible lower-cost concepts with identifiable upside potential (MIF and others)

Develop technologies with potential to drastically reduce cost for tokamaks, stellarators, IFE

Timeliness constraint

↓

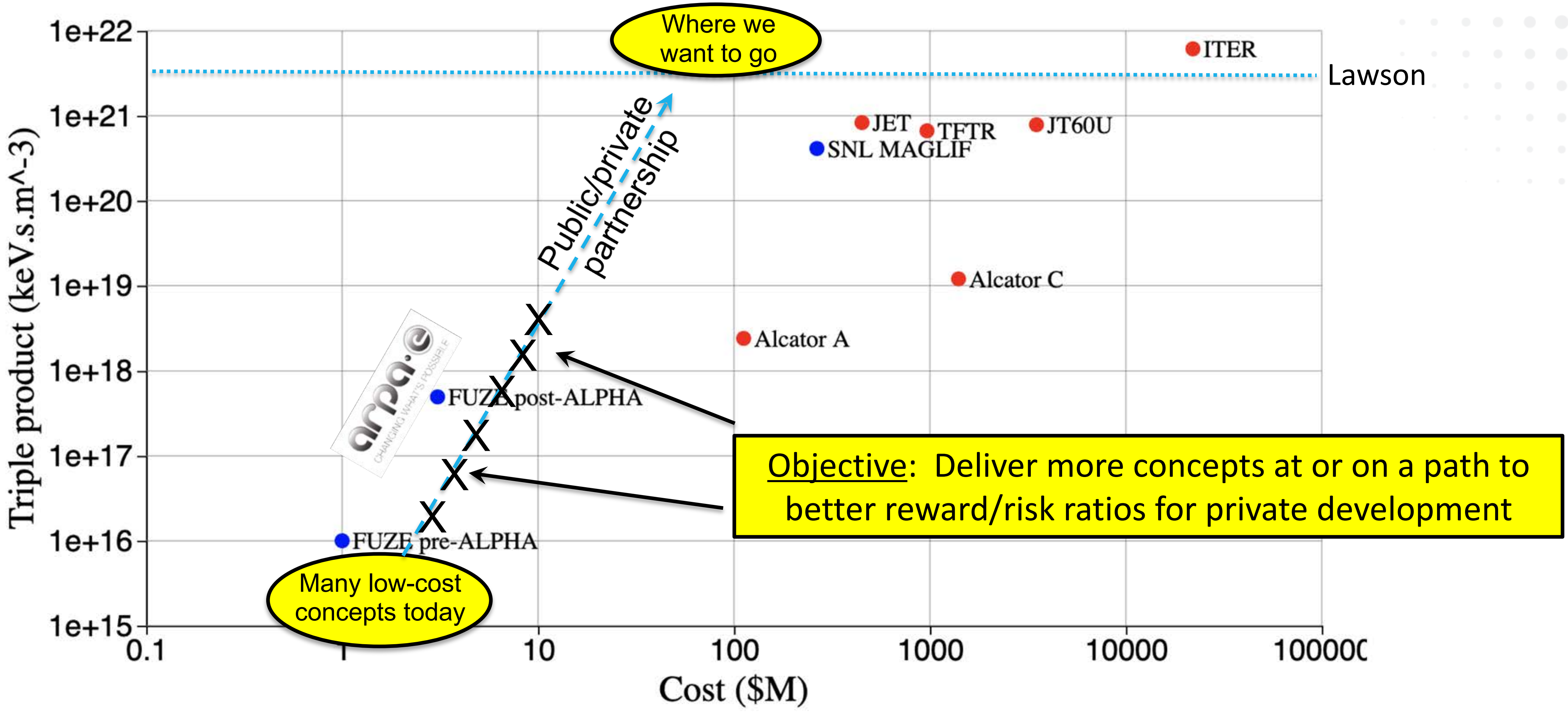
Catalyze technology/engineering development for commercially motivated fusion concepts

Priorities: plasma-facing/blanket, tritium-processing, and high-duty-cycle enablers

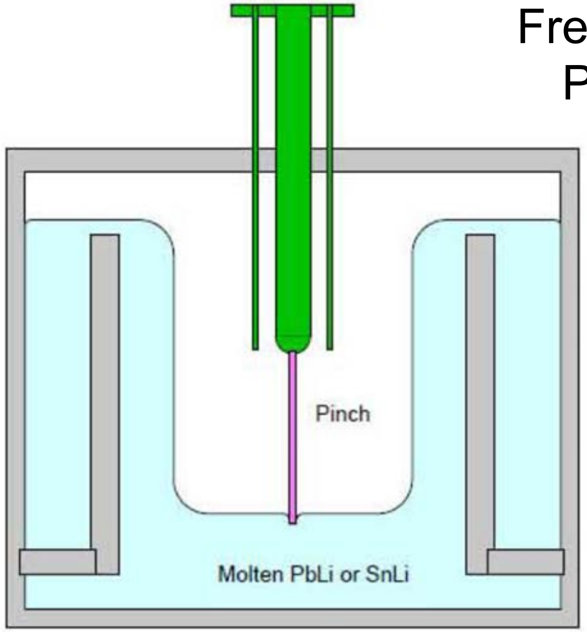
see Request for Information
(50 responses, will provide to FES/CPP PC for responses with authors' permission)

*OCC = overnight capital cost

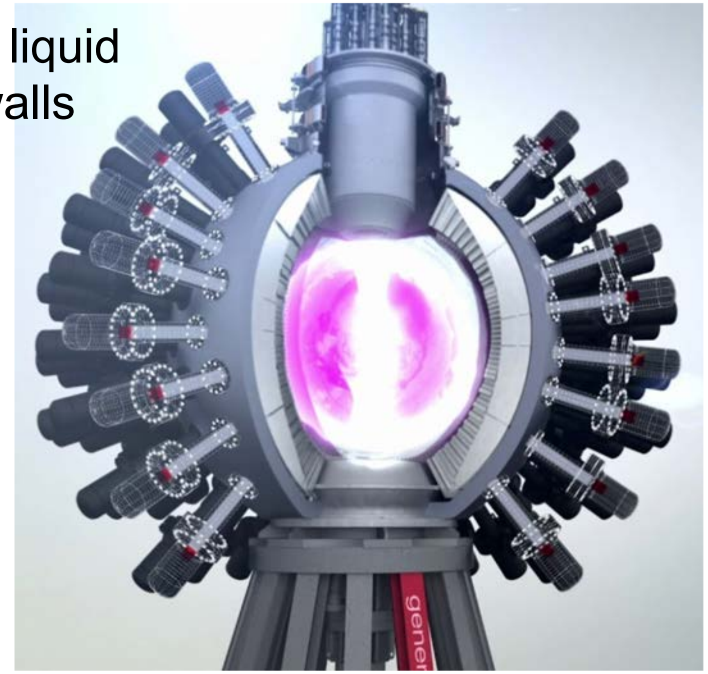
Potential program A: Develop credible fusion concepts that may cost ~$\mathcal{O}$($100M) for net gain and ~$\mathcal{O}$($1B) for grid-ready demo

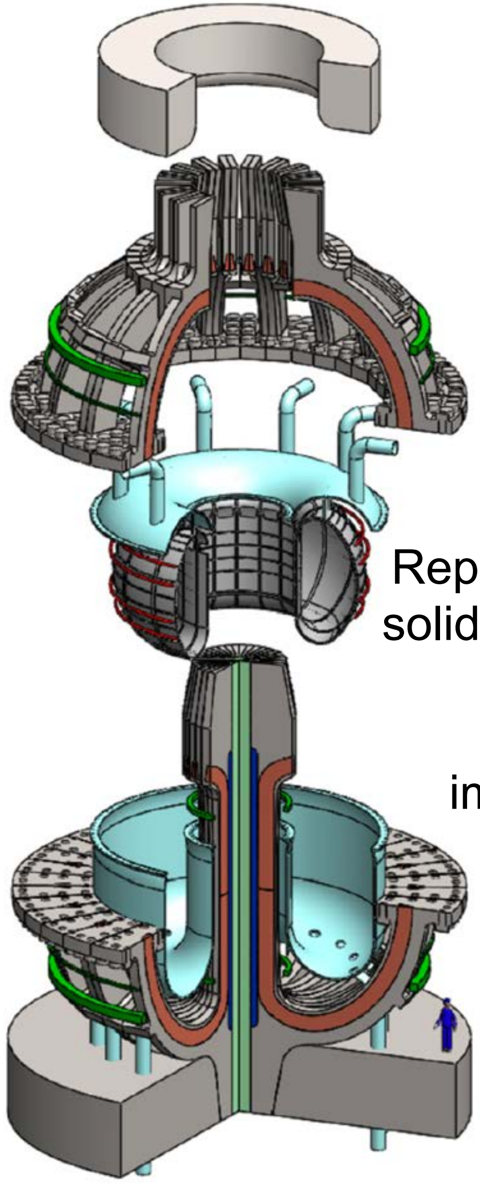


Potential program B: Catalyze enabling-technology solutions to common challenges of commercially motivated fusion concepts



Free-surface liquid PbLi first walls





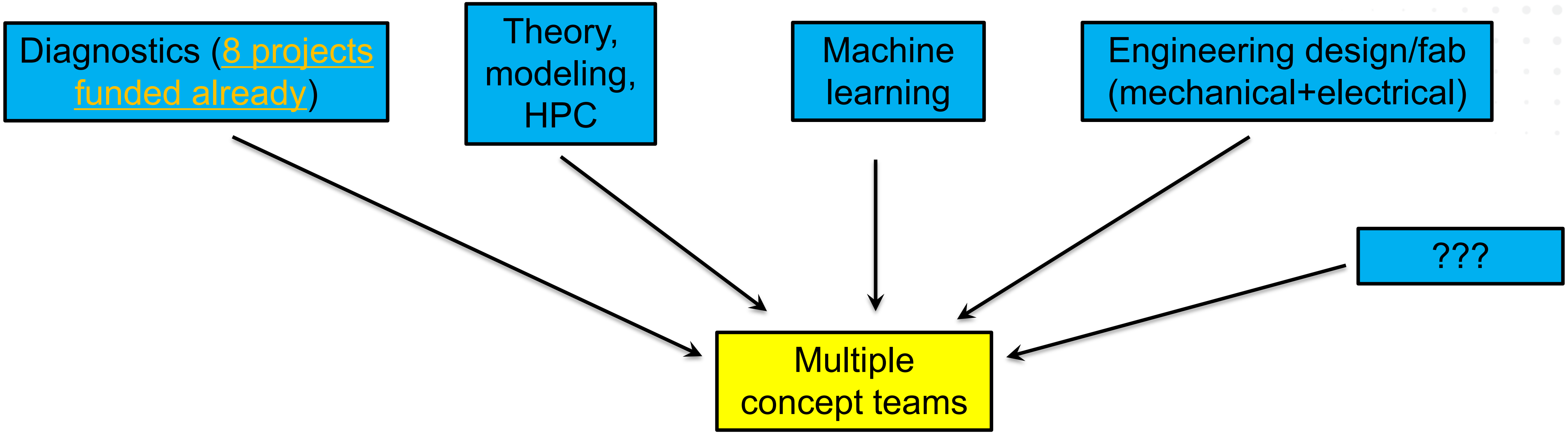
Replaceable solid first wall

FLIBE immersion blanket

- Engage outside communities
- Enable use of thick liquid blankets
- Tritium process intensification to minimize tritium inventory
- Accelerated subscale material testing
- Beyond solid divertors
- Exploit advances in modern power electronics
- Advanced fuels and power cycles

Different but synergistic challenges/requirements compared to ITER-based DEMO

ARPA-E is exploring idea of "capability teams" to support fusion concept teams



Leverage the best expertise	Avoid reinventing the wheel by each concept team	Stretch limited $$	Build public-private partnership

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Fusion T2M plans at ARPA-E: Smoothing the pathway to fusion commercialization

- Support studies to identify first markets for fusion at a range of unit size and cost
- Weave in programmatic structure and incentives for public-private partnering
- Build finance scaling through investor engagement
- Help establish fusion regulatory certainty and public acceptance

SC/FES legislation of interest/relevance to ARPA-E

- H.R. 589 “Department of Energy Research and Innovation Act” (became public law no. 115-246 on 9/28/2018):
  - SC/ARPA-E coordination on fusion energy
  - Support IFE and a portfolio of alternative and enabling fusion energy concepts
- S. 97 “Nuclear Energy Innovation Capabilities Act of 2017” (became public law no. 115-248 on 9/28/18)
  - Extensive language on memorandum of understanding between DOE and NRC to benefit advanced-reactor testing, development, and demonstration including fusion
- Pending FY20 Senate appropriations language on private-public partnership:
  - Up to $20M for INFUSE
  - Up to $20M to initiate a (NASA/COTS-like) cost-share program for integrated prototype demonstrations over the next 5 years

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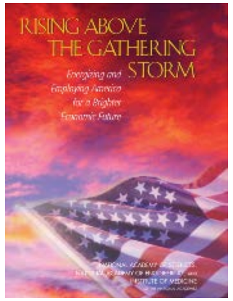
History of ARPA-E

In 2007, The National Academies recommended Congress establish an Advanced Research Projects Agency within the U.S. Department of Energy to fund advanced energy R&D.



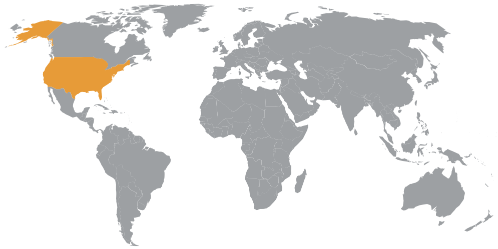
2007

Rising Above the Gathering Storm **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

America COMPETES Act **Signed** – authorizing the creation of ARPA-E

2009

American Recovery & Reinvestment Act **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects

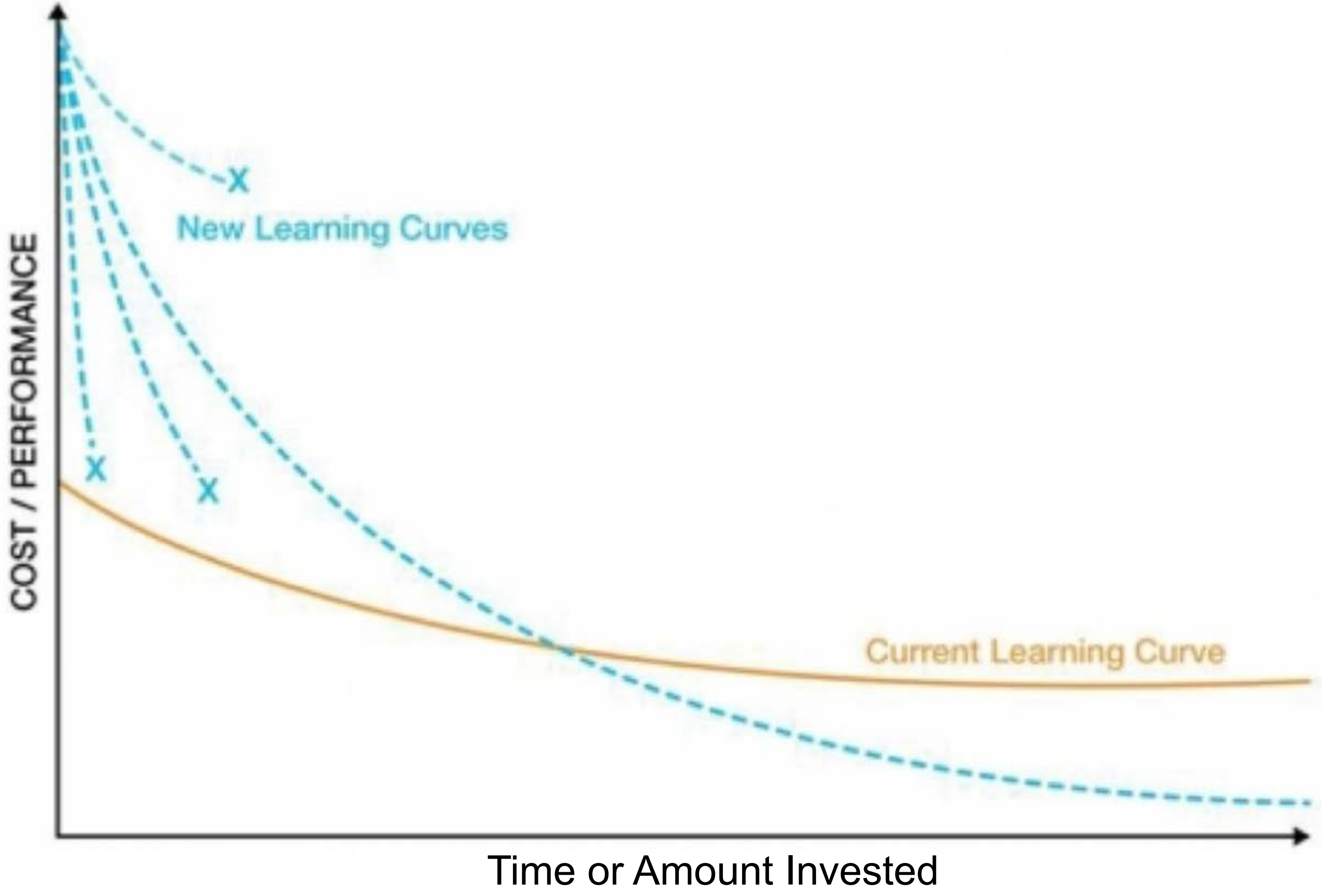


2019

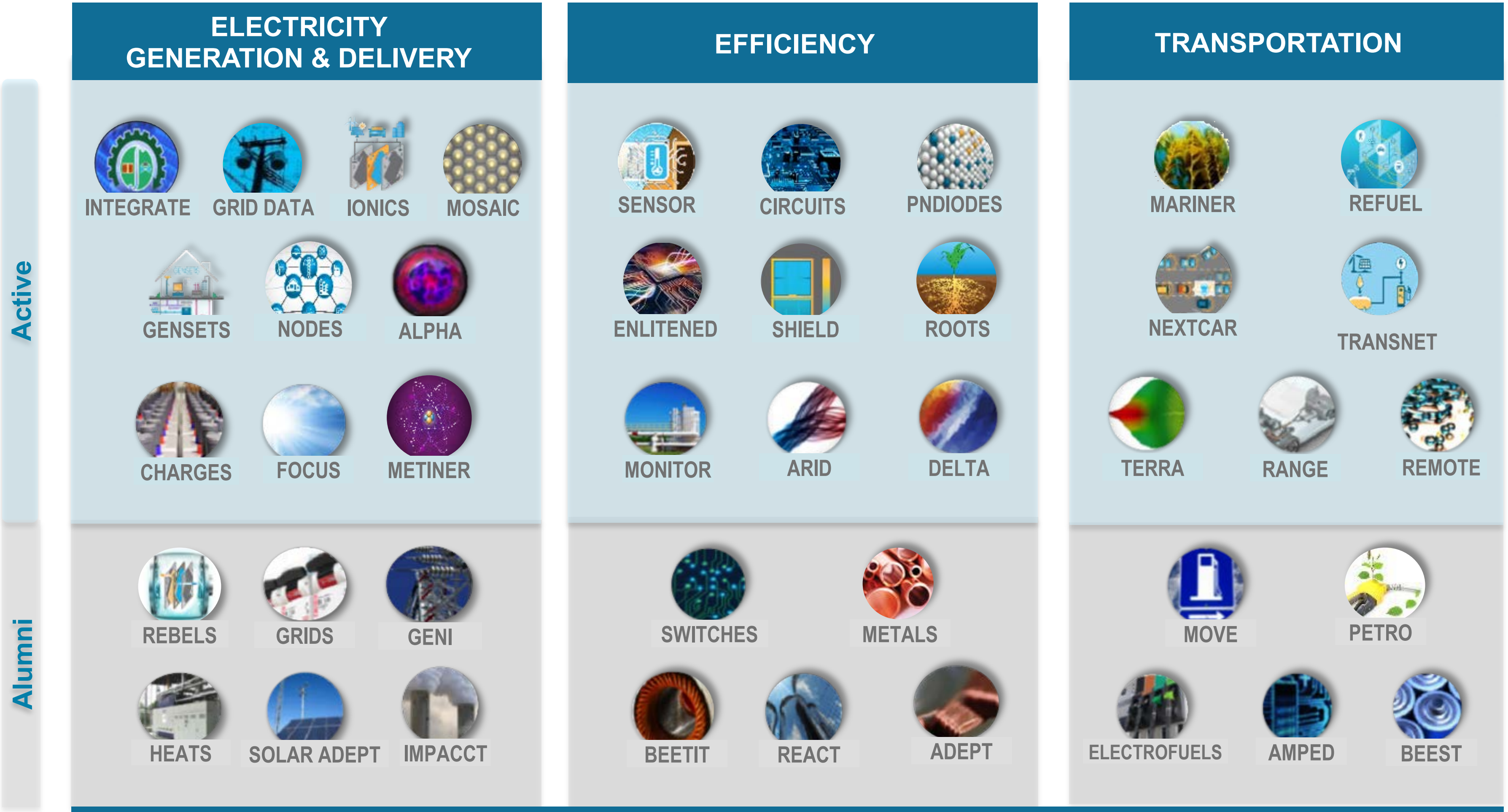
800+ Awards
47+ Programs

Current Funding:
US$366M
(FY19)

ARPA-E funds transformative, off-roadmap energy R&D with the goal of disrupting "current learning curves"

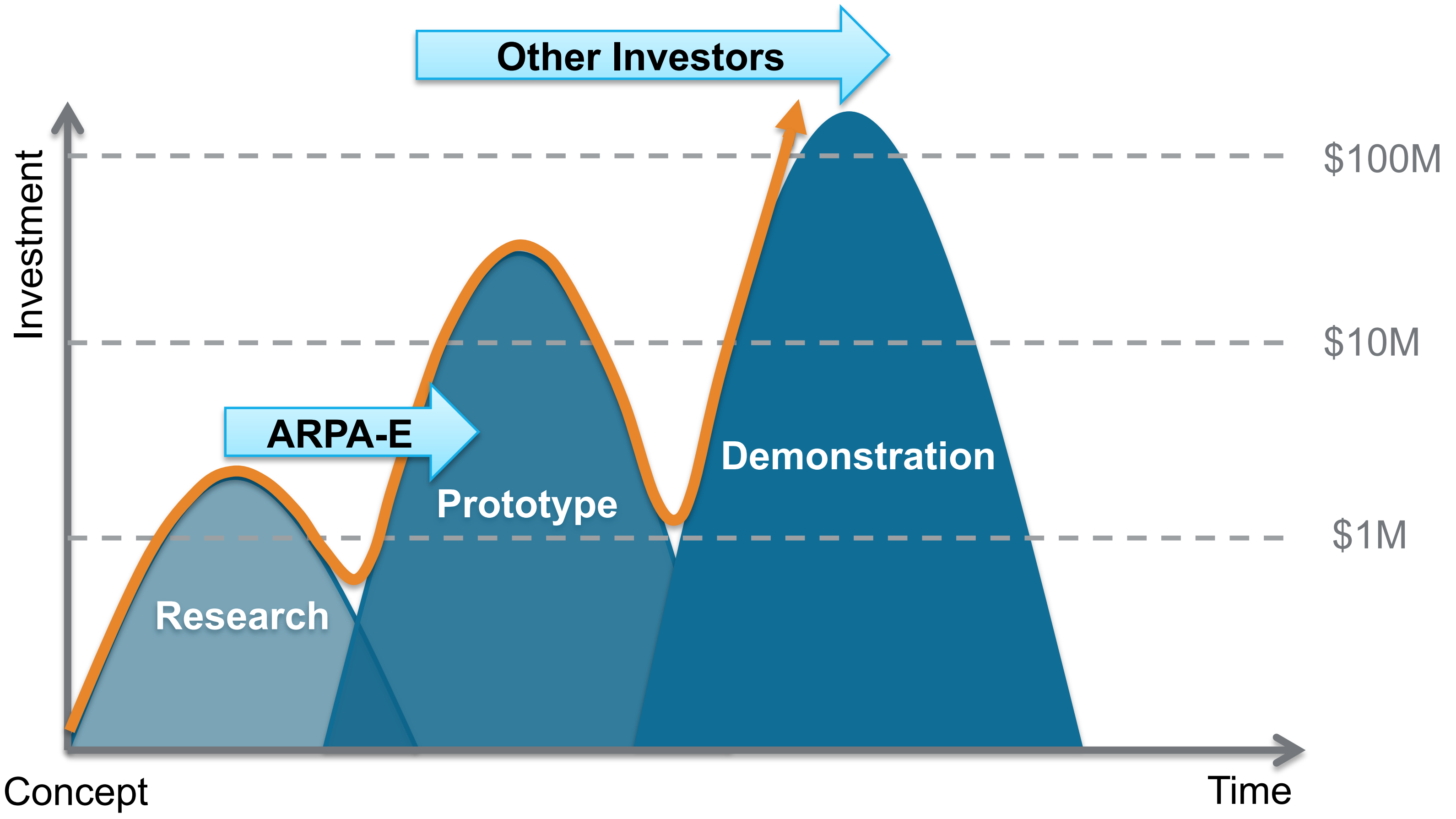


Limited-term program directors formulate, pitch, and execute "focused programs" that are each nominally 3 years, $30M total



OPEN 2009, 2012, 2015 & 2018 Solicitations
Complement Focused Programs

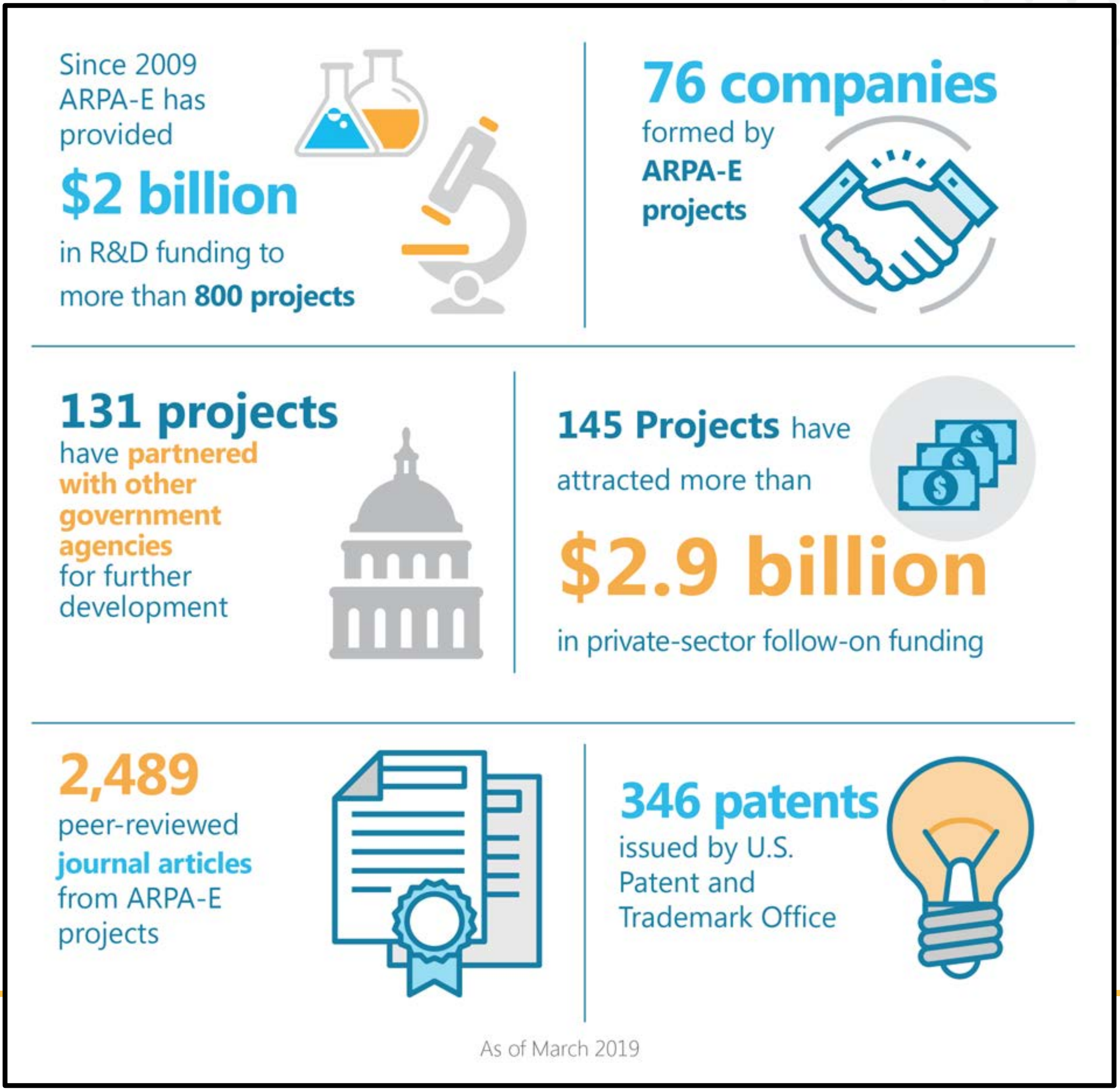
ARPA-E aims to create a “mountain of opportunity” in transformative energy technologies



Public-private partnering is at the core of ARPA-E's mission and program formulation/execution

Metrics:

- Private-sector follow-on funding
- New company formation
- Partnership with other government agencies
- Publications, inventions, patents



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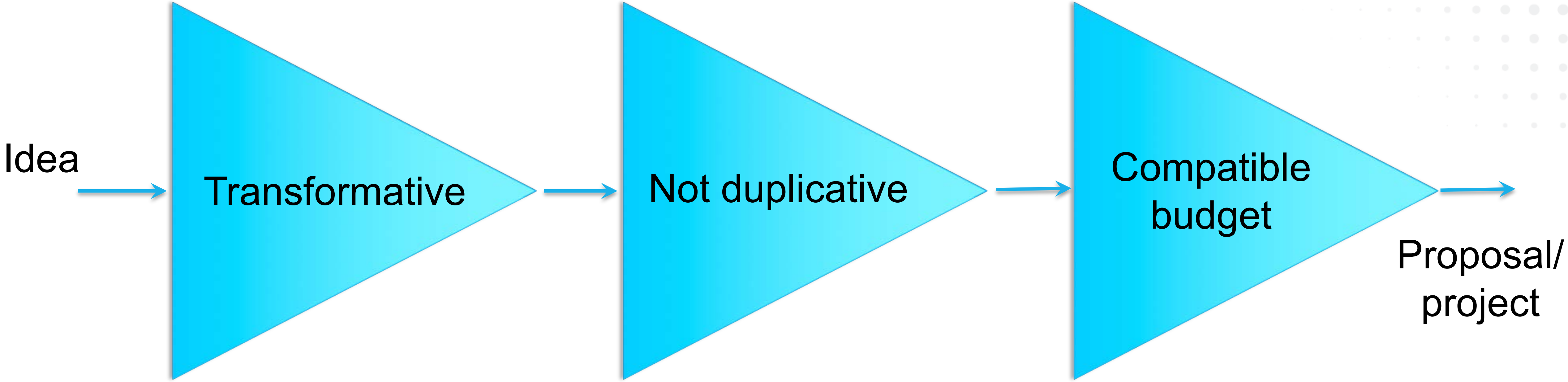
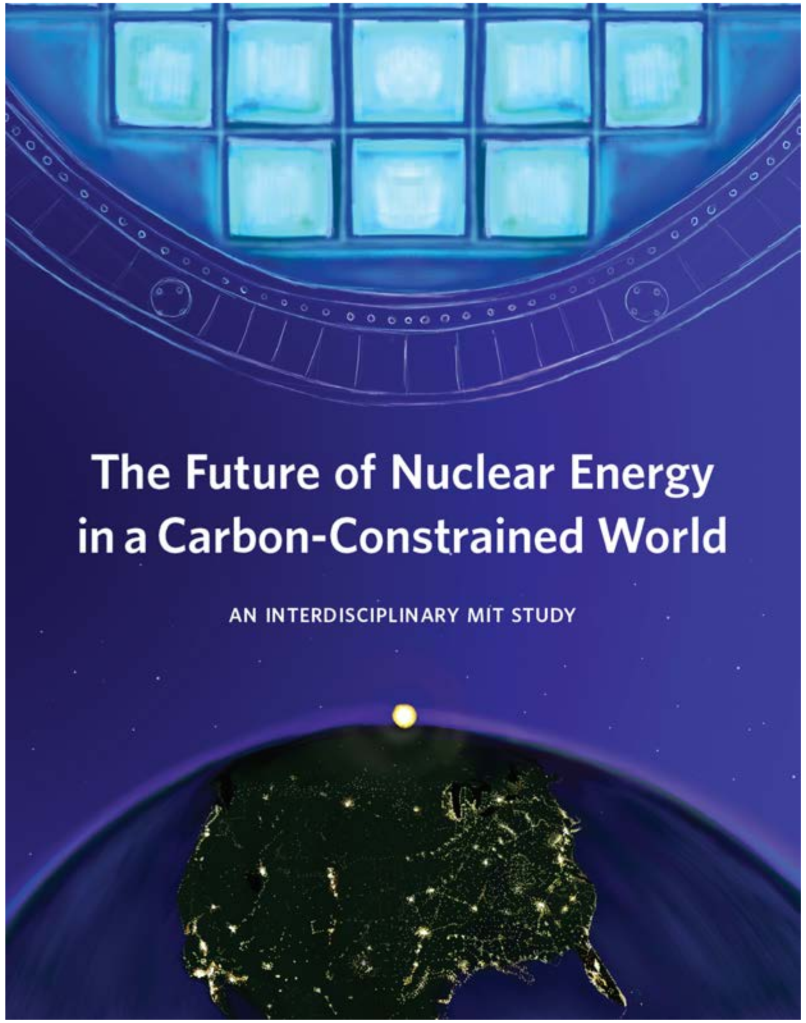
What makes a good ARPA-E proposal/project?

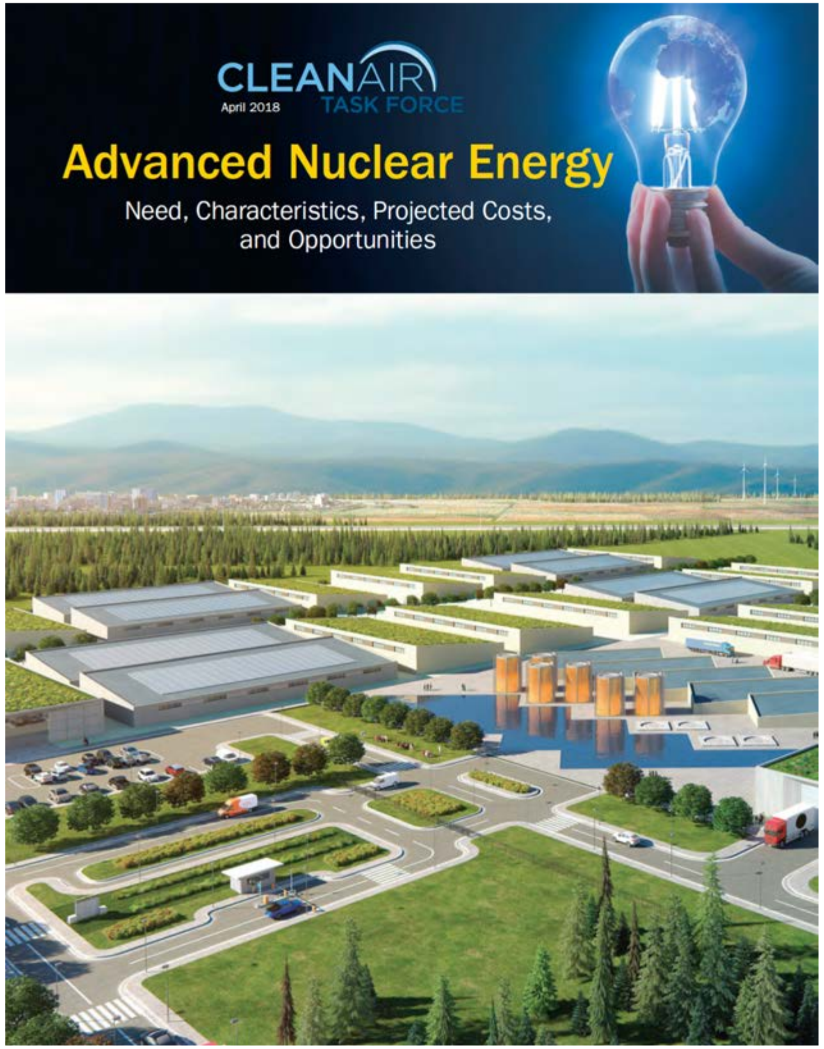


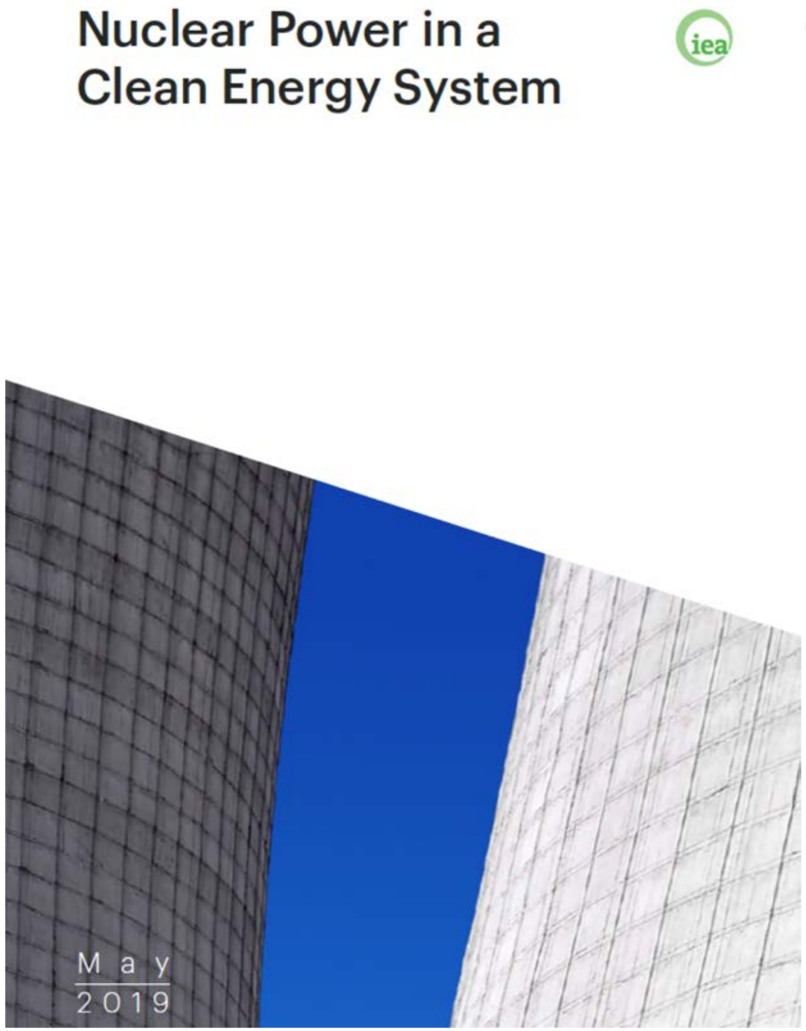
Potential to disrupt development trajectory based on present state-of-the-art projections

Impactful project result for ≤$10M (federal funds), ≤3 years that will catalyze further support/effort

Fusion must learn from fission: (1) lower the cost/complexity, (2) understand markets, (3) achieve regulatory certainty, and (4) earn public acceptance



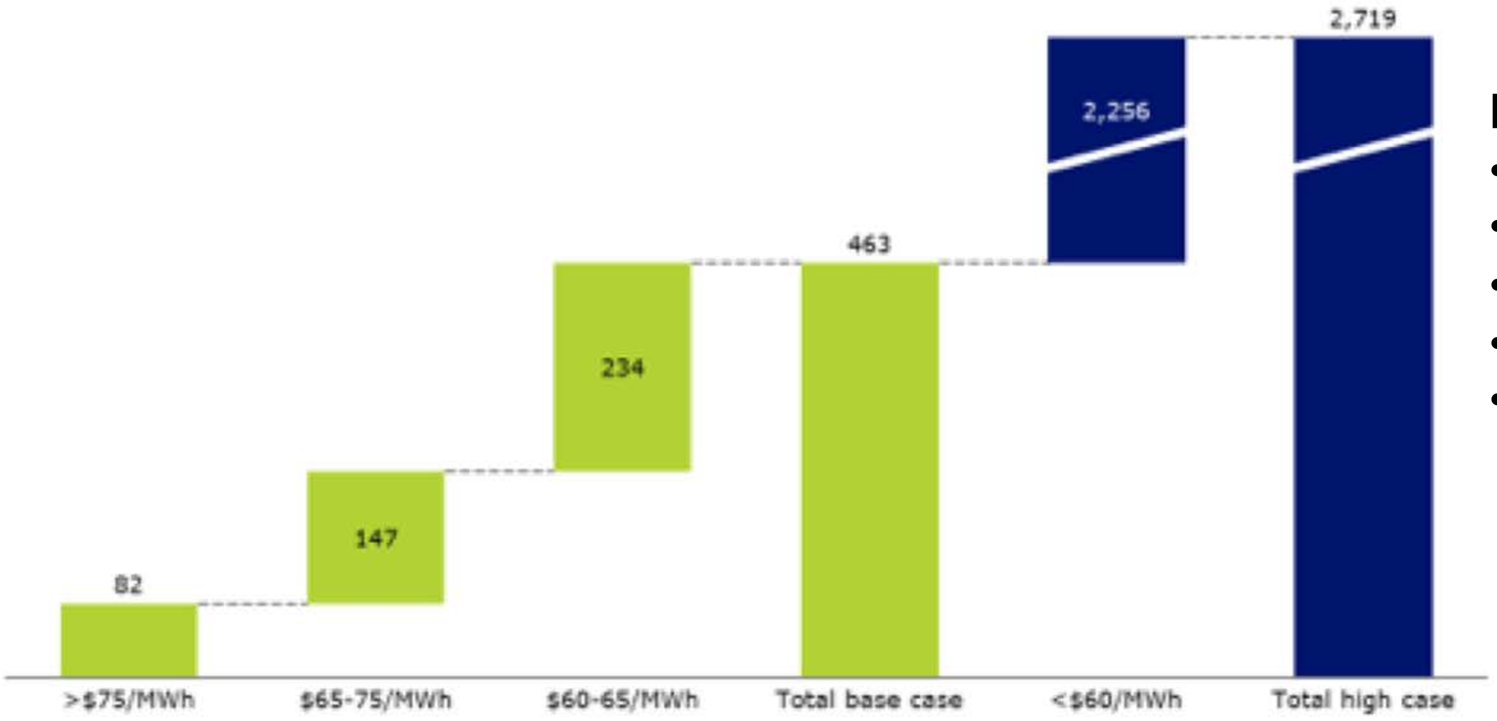




Markets/cost: One study suggests that, in 2030, ~465-GWe exist for fusion at >$75/MWh, and ~2.7-TWe exist at <$60/MWh

The likely addressable market for fusion in the 2030s amounts to ~465 GW globally, with a much bigger potential of ~2,720 GW if fusion can compete with fossil fuels below $60/MWh

Total estimated addressable market for fusion (GW) at different price levels in a high electrification scenario



Examples:

- Alaskan village: $400/MWh
- DoD base: $200/MWh
- Singapore: $130/MWh
- Germany: $60/MWh
- Texas: $3/MWh

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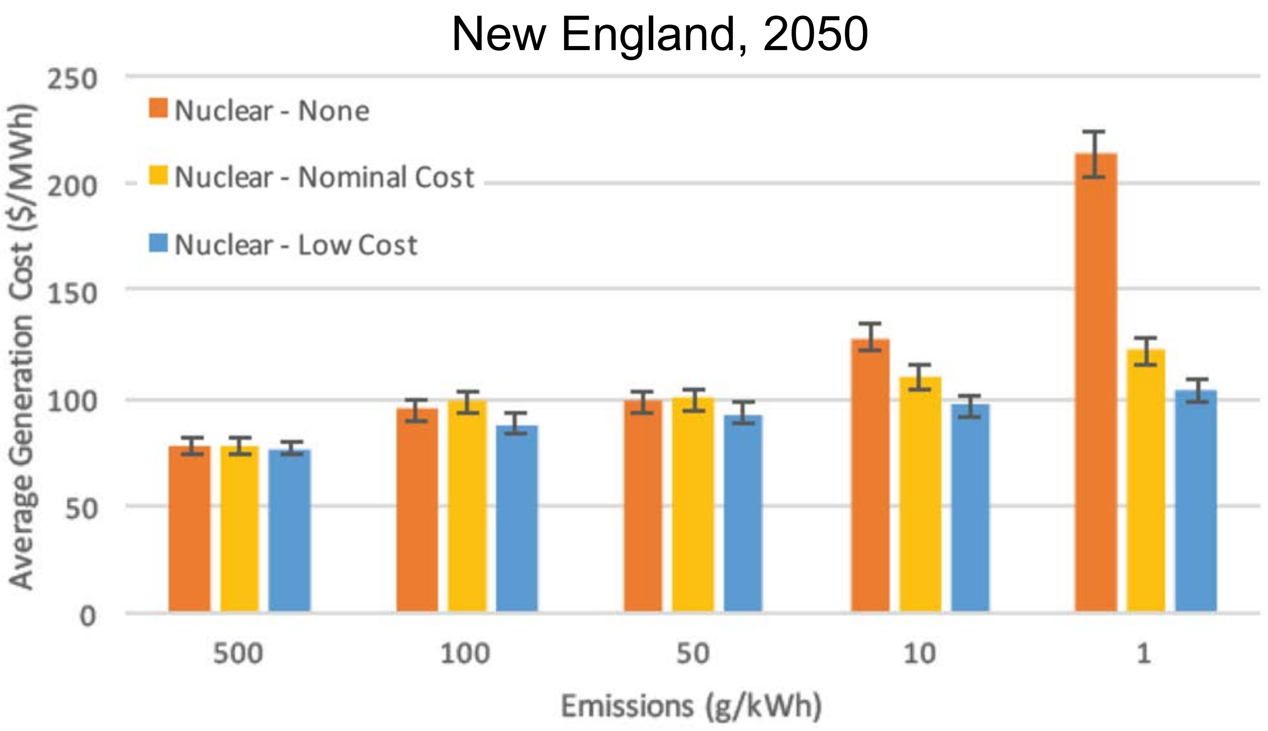
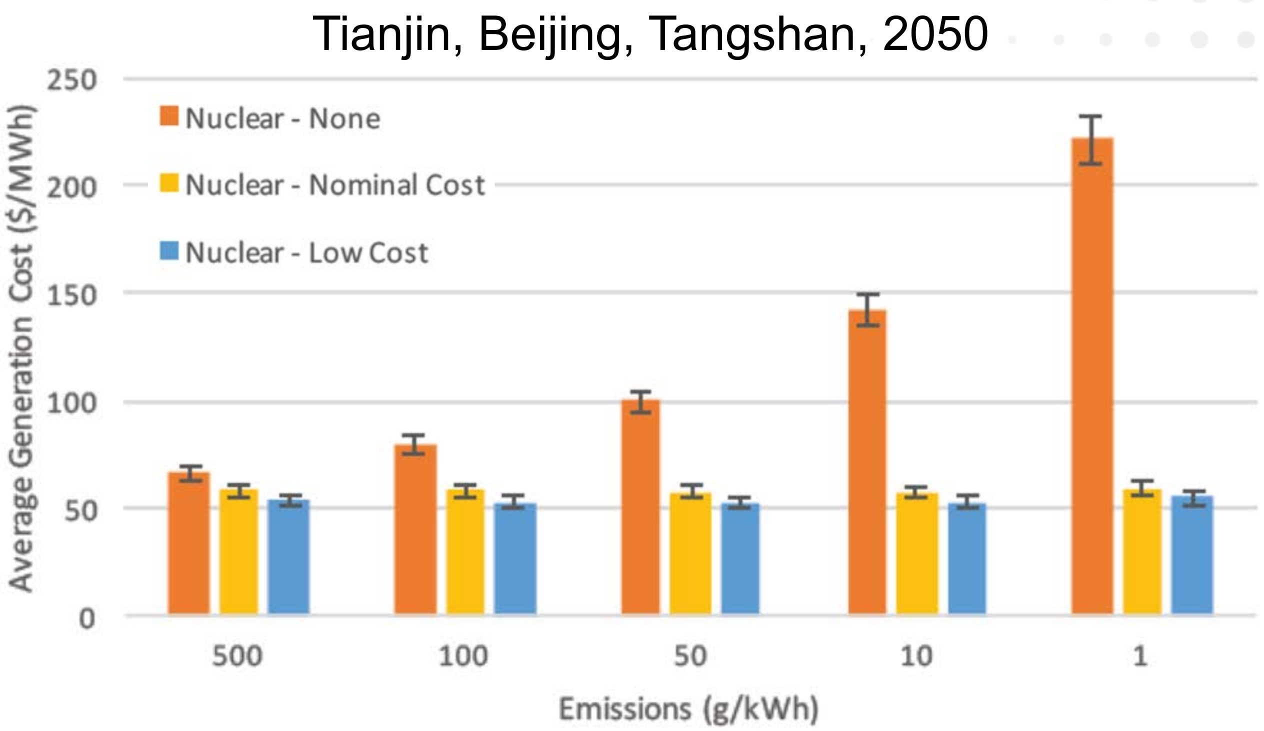
Source: Electrification and decarbonization: the role of fusion in achieving a zero-carbon power grid (from SYSTEMIQ, July 12, 2019)

Firm power sources (i.e., meets demand over seasons and long duration) needed for cost-effective, low-carbon grid

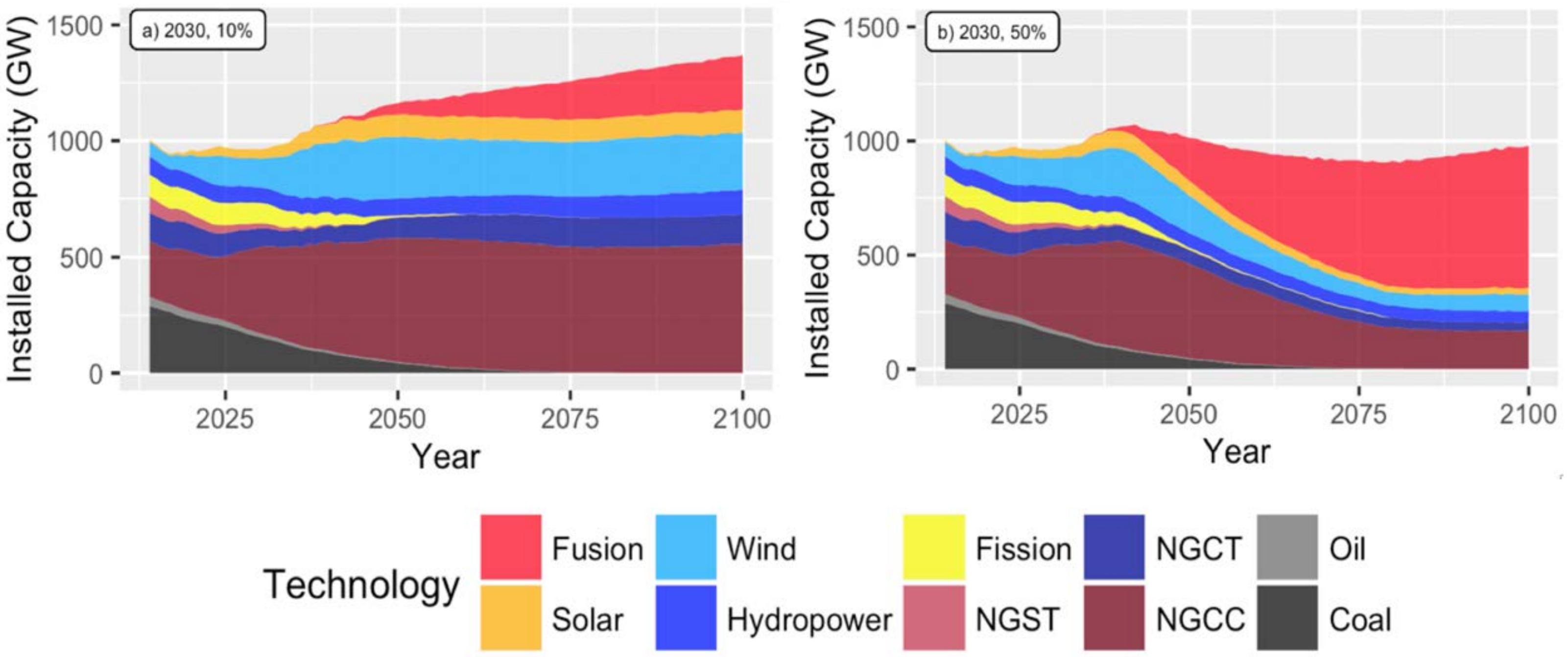




From "The Future of Nuclear Energy in a Carbon-Constrained World, An Interdisciplinary MIT Study," MIT Energy Initiative (2018), p. 13.

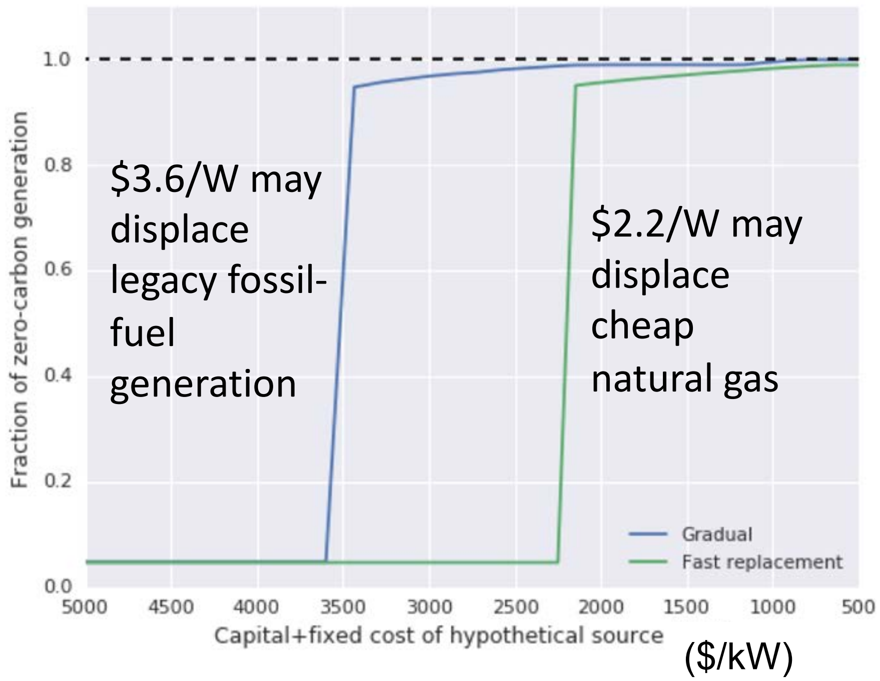
Fusion programs at ARPA-E are informed but not overly constrained by market awareness

To impact 21st-century markets, fusion must be solved and adopted quickly.



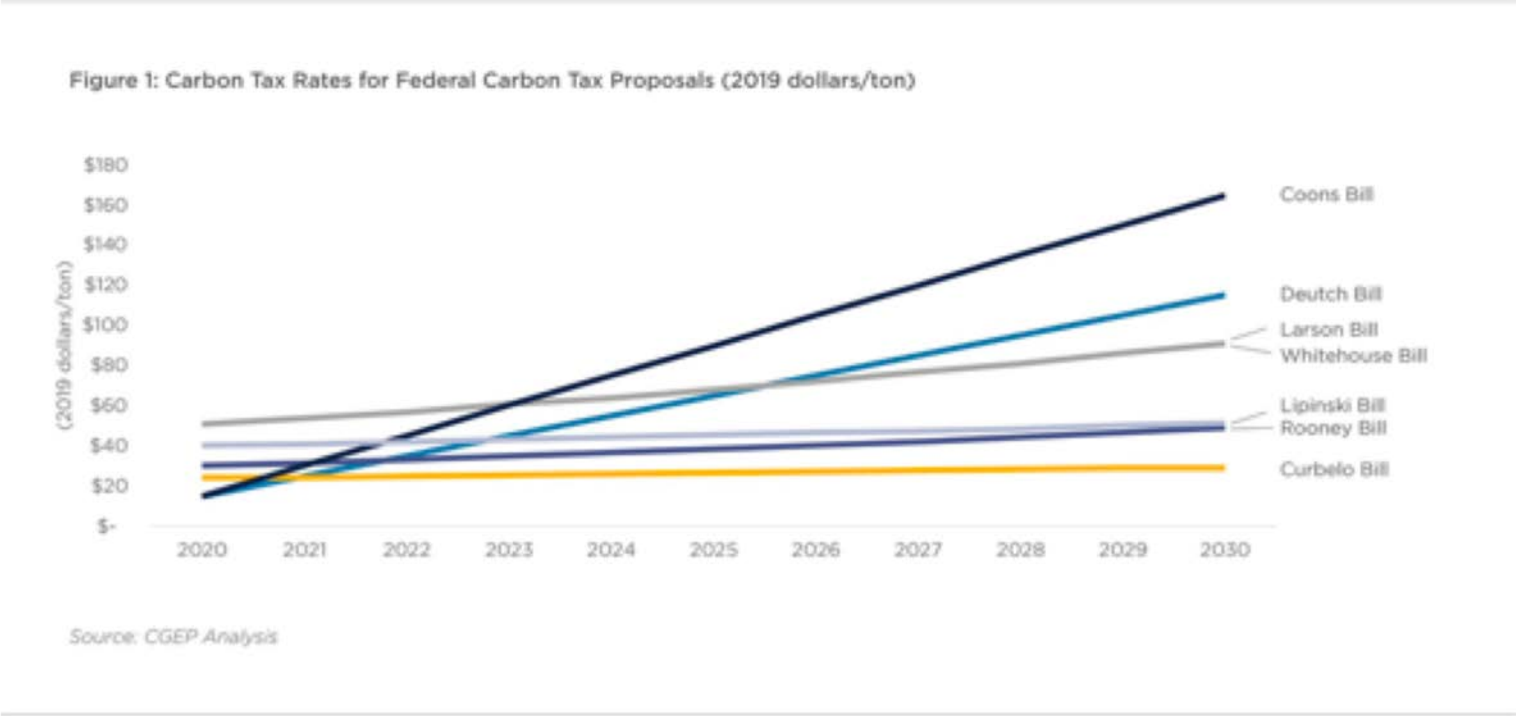
L. Spangher, J. S. Vitter and R. Umstattd, "Characterizing fusion market entry via an agent-based power plant fleet model," Energy Strategy Reviews 26, 100404 (2019).

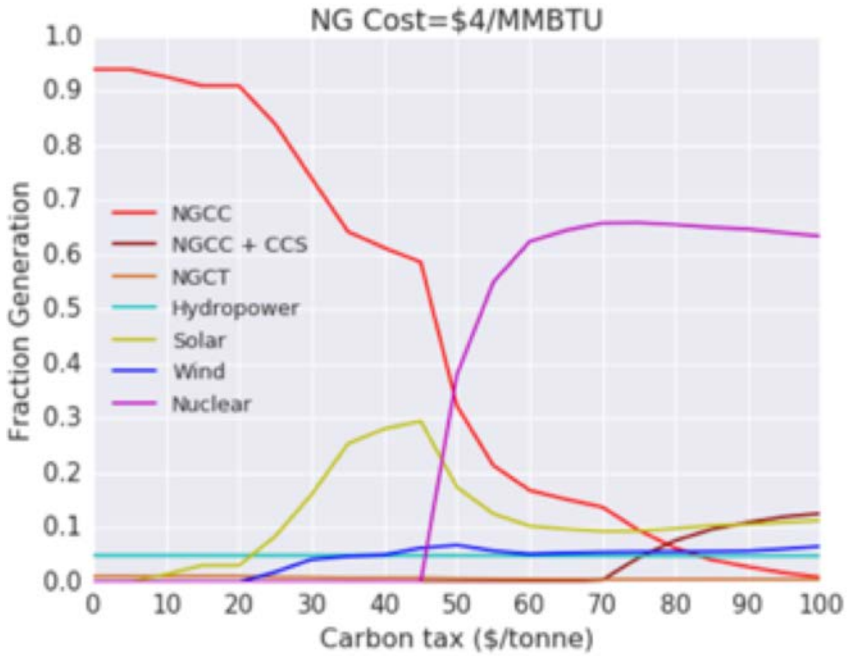
What capital cost is needed for a hypothetical zero-carbon, 100%-capacity-factor electricity source to be adopted quickly (i.e., to displace fossil fuels)?



Platt, John and Pritchard, J. Orion and Bryant, Drew, Analyzing Energy Technologies and Policies Using DOSCOE (August 8, 2017). Available at http://dx.doi.org/10.2139/ssrn.3015424.

Carbon tax of >$50/ton could greatly expand the market for fusion (based on modeling of fission in competitive market)



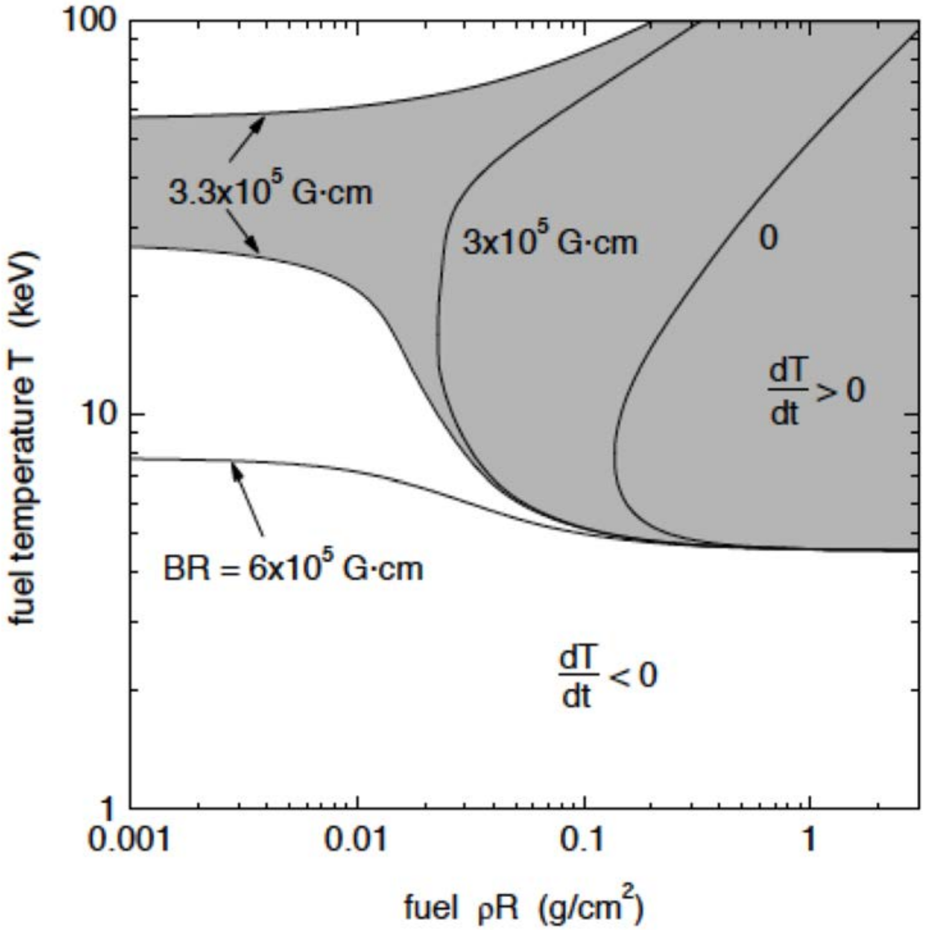


https://twitter.com/noahqk/status/1157343492332539910

[Analyzing Energy Technologies and Policies Using DOSCOE]

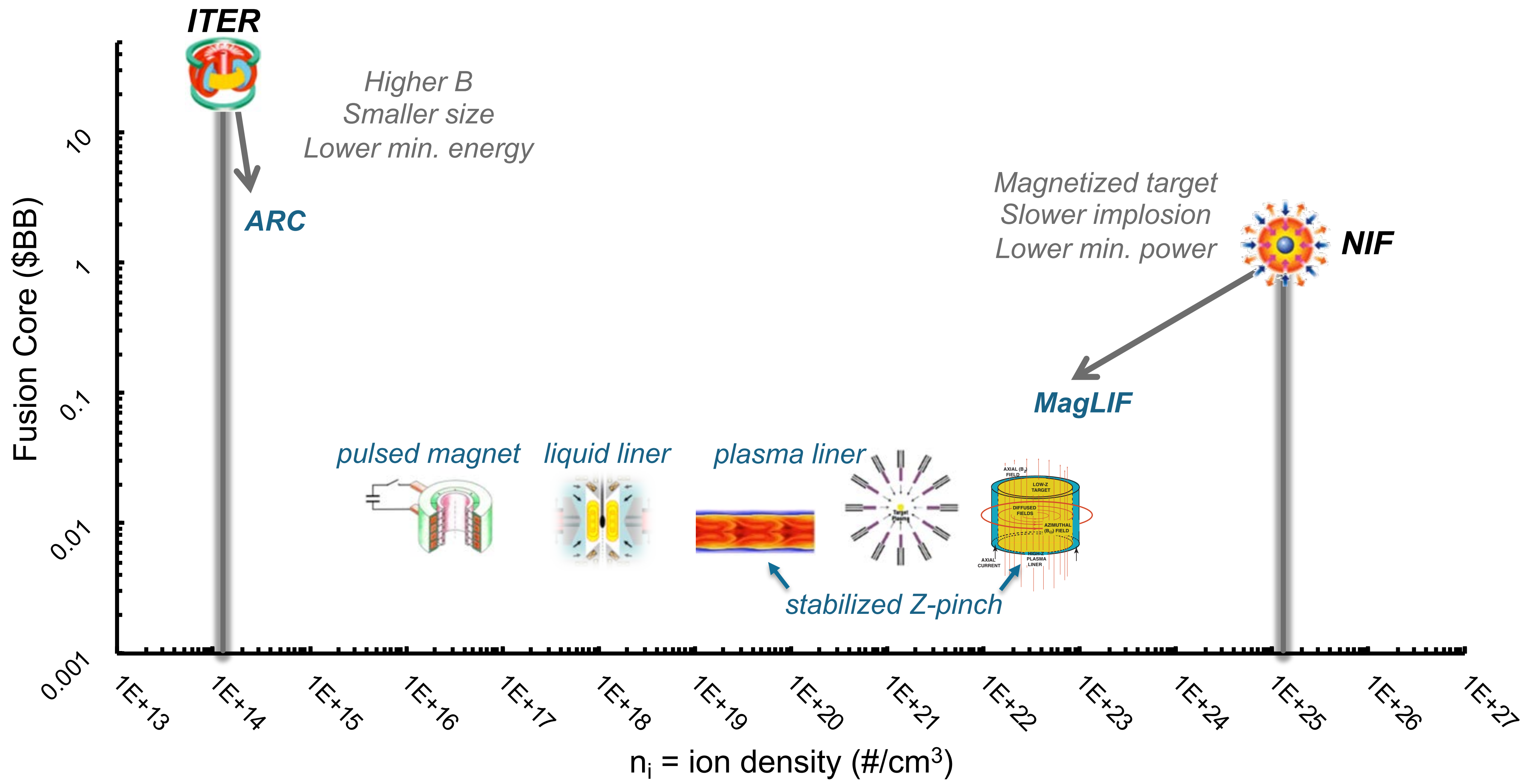
ALPHA focused on pulsed, magnetized, intermediate-density fusion (MIF and z-pinch variants) → lowers ignition requirements

Magnetic field dramatically reduces areal density (and therefore predicted facility cost) required for pulsed ignition



M. M. Basko et al., Nucl. Fus. **40**, 59 (2000)
I. R. Lindemuth & R. E. Siemon, Amer. J. Phys. **77**, 407 (2009)

Fusion concepts studied within the ALPHA portfolio spanned ~6 orders of magnitude in fuel density



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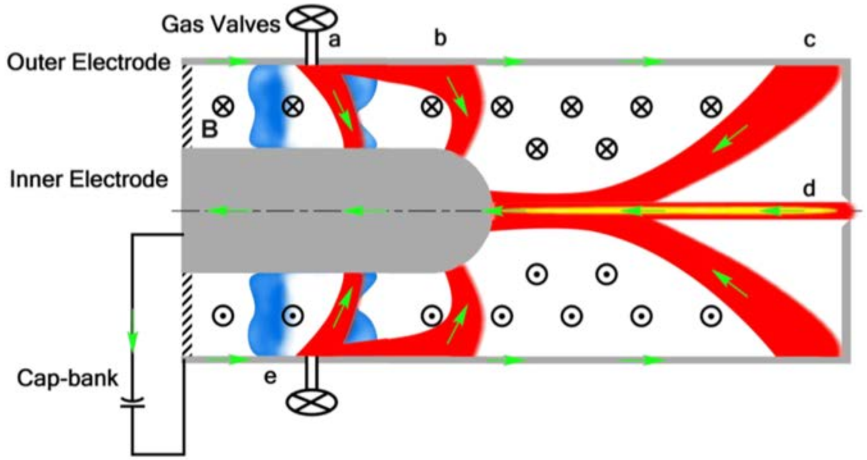
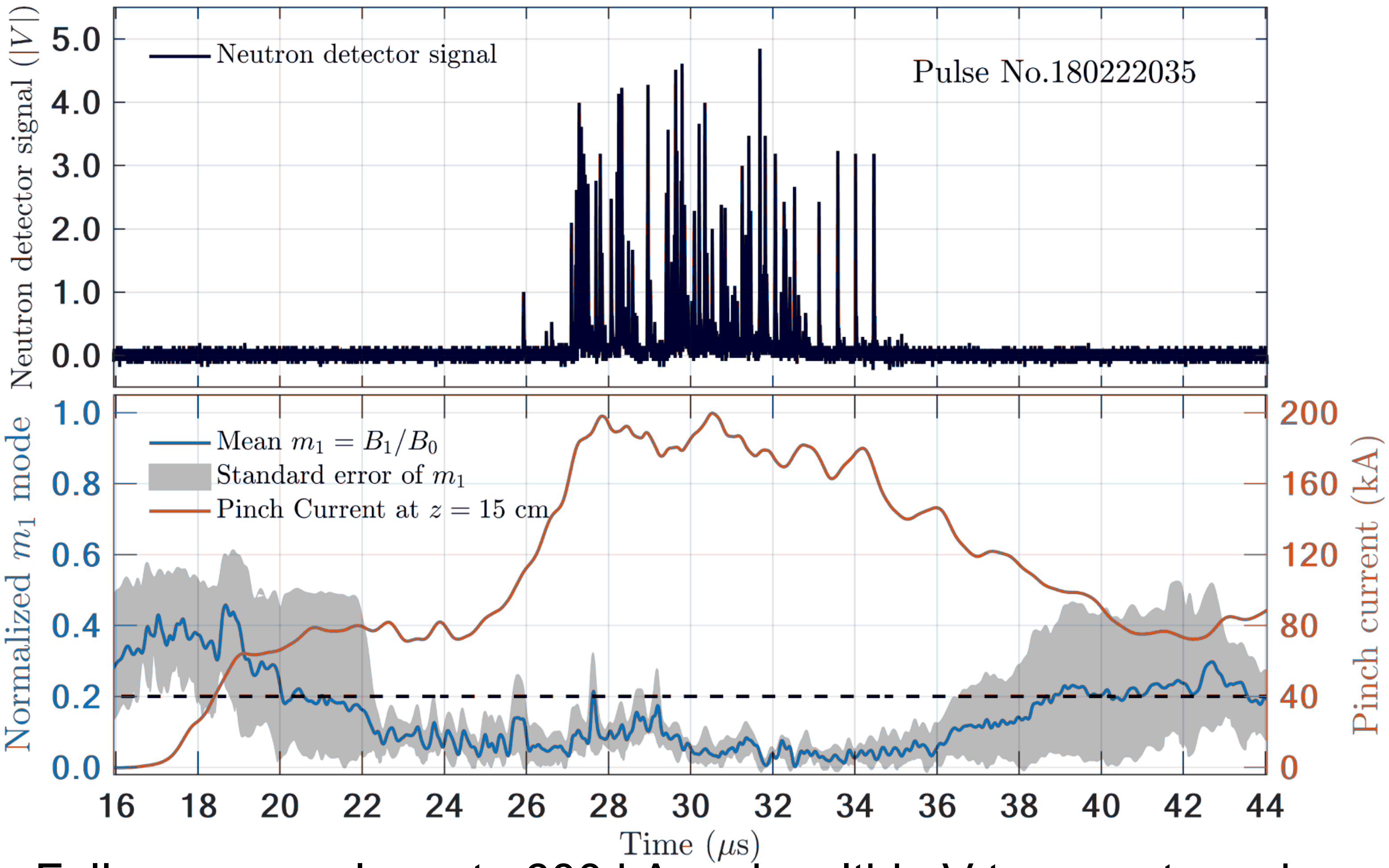
ALPHA concept: Sustained neutron production in a sheared-flow stabilized Z pinch, consistent with thermonuclear DD fusion



	n_i (m^{-3})	T_e=T_e (keV)	τ_E (µs)	$nT\tau_E$ (keV s/m^3)
Pre-ALPHA	3e22	0.075	5	1e16
ALPHA	1e23	~1.0	~5	~5e17



Follow-on: scale up to 600 kA and multi-keV temperatures by spin-out Zap Energy (ARPA-E OPEN 2018 program)

UNIVERSITY of WASHINGTON

Lawrence Livermore National Laboratory

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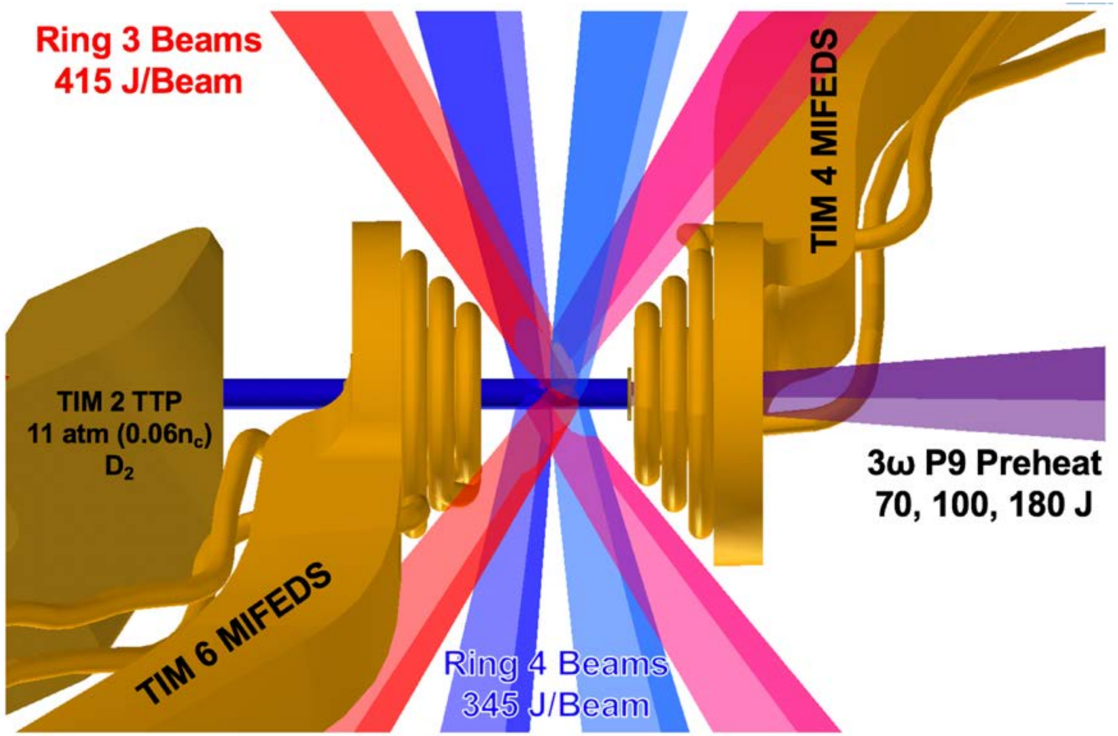
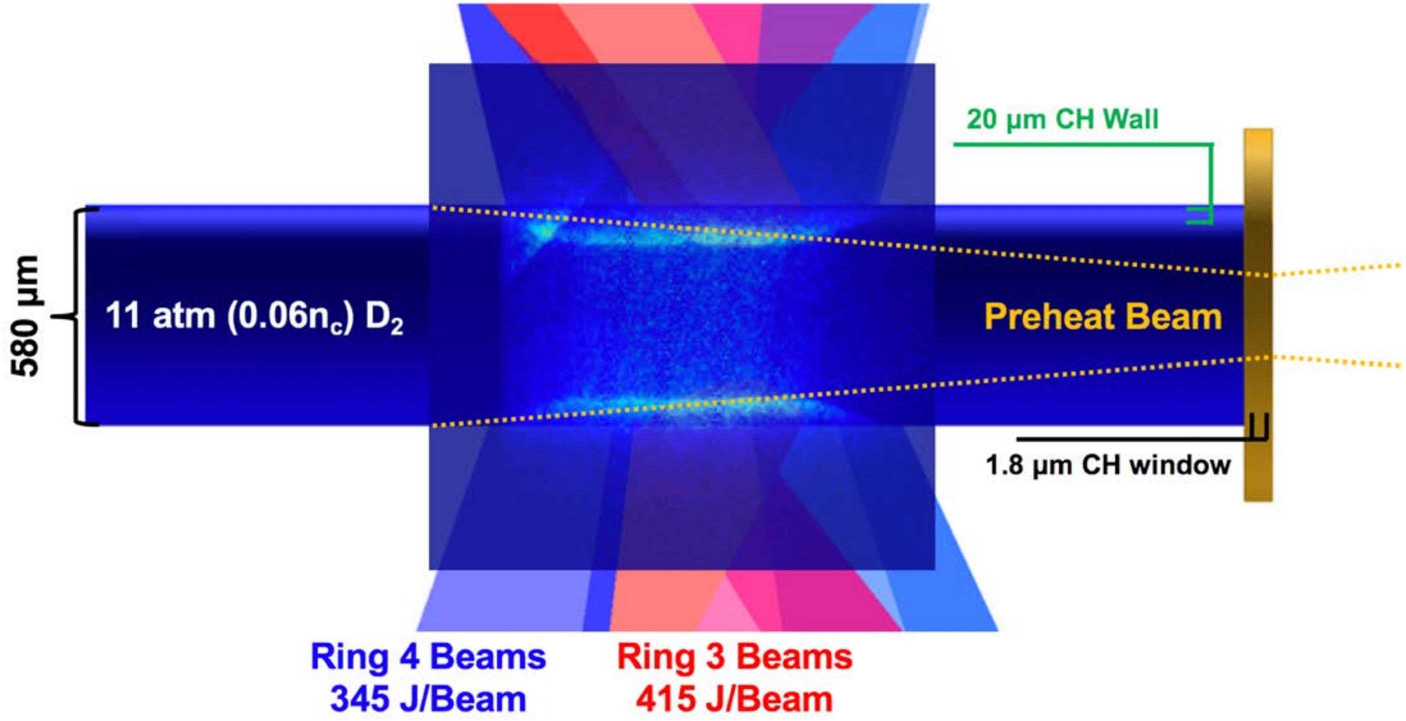
U. Shumlak et al., Phys. Plasmas **24**, 055702 (2017)
Y. Zhang et al., PRL **122**, 135001 (2019)

ALPHA applied science: Development of the OMEGA "mini-MagLIF" platform to explore MIF science at fusion conditions





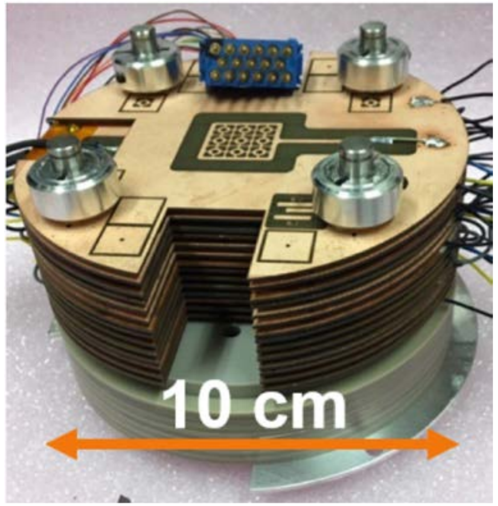
With axial field and laser pre-heat, T_i > 2.5 keV, Y_{DD} > 10^{10} neutrons

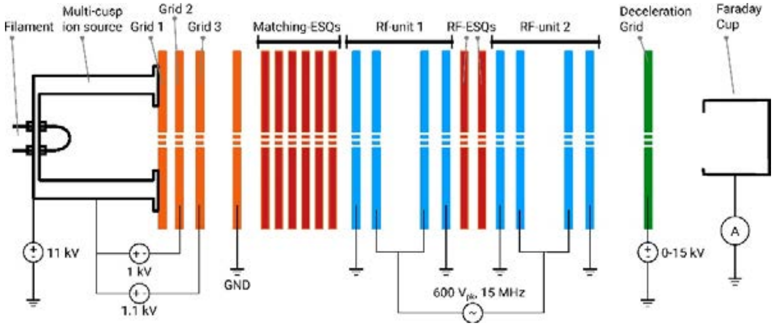
Sandia National Laboratories UR LLE

D. H. Barnak et al., Phys. Plasmas **24**, 056310 (2017)
J. R. Davies et al., Phys. Plasmas **24**, 062701 (2017)
E. C. Hansen et al., Phys. Plasmas **25**, 122701 (2018)
J. R. Davies et al., Phys. Plasmas **26**, 022706 (2019)

ALPHA drivers: demonstration of two new potential MIF drivers, MEMS ion accelerator and plasma guns with preionization

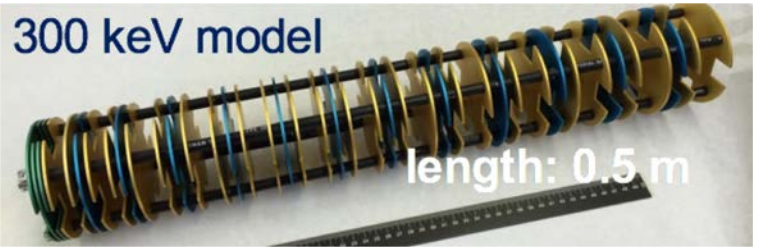
Compact, low-cost, high-power ion beams





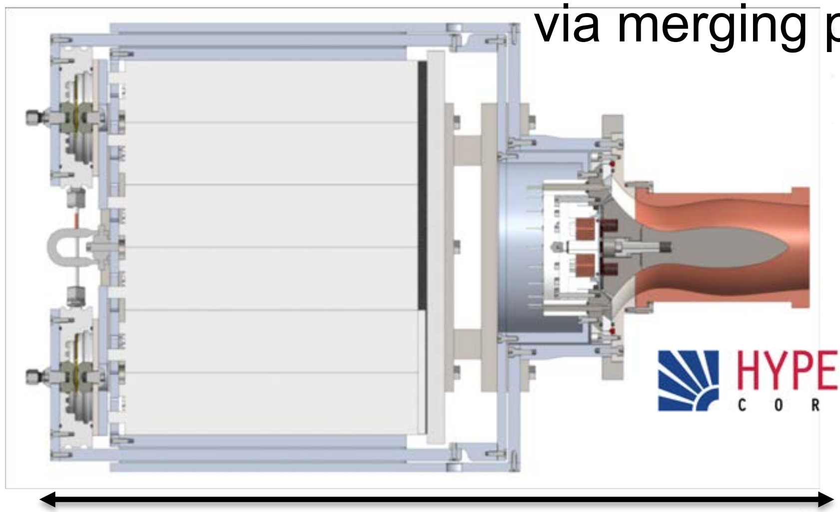
Demonstrated 2.6 kV/gap,
10.2 kV, 3×3 beam array

Follow-on: scale up to 1 MV/m and >100 mA
(ARPA-E OPEN 2018 program)



BERKELEY LAB
Lawrence Berkeley National Laboratory

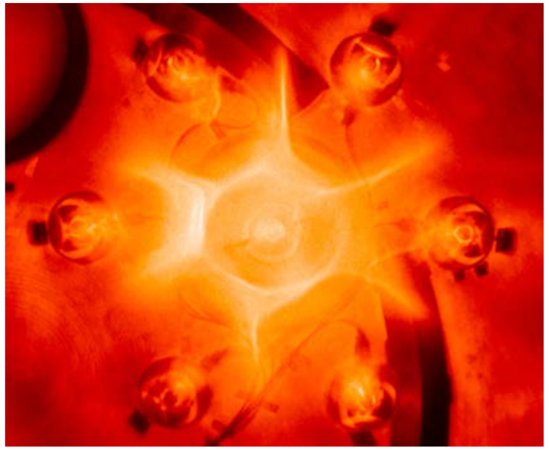
Plasma guns for plasma-liner formation via merging plasma jets

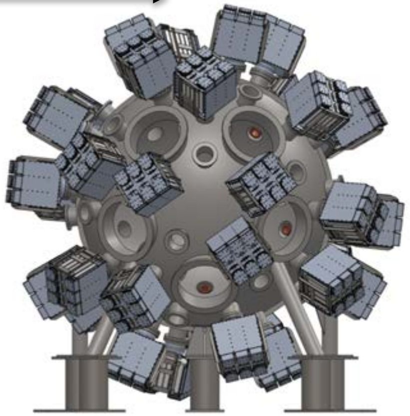


~80 cm

1 mg mass
50 km/s
$>10^{16}$ cm^{-3}

HYPERJET FUSION CORPORATION





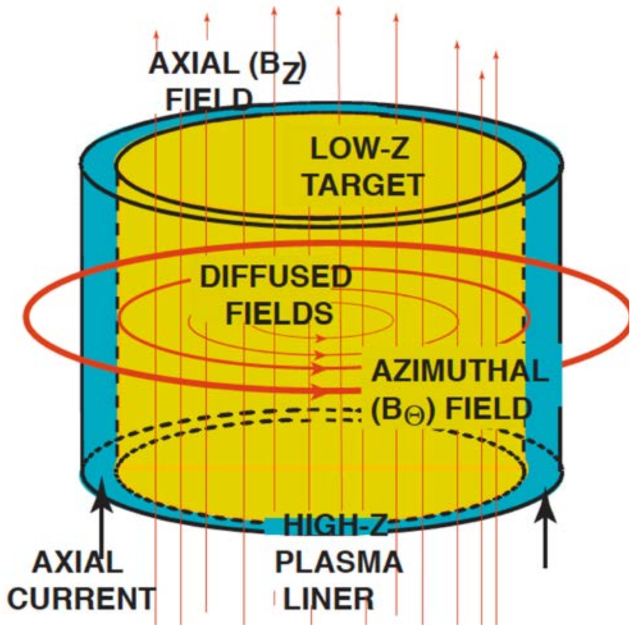
Los Alamos NATIONAL LABORATORY

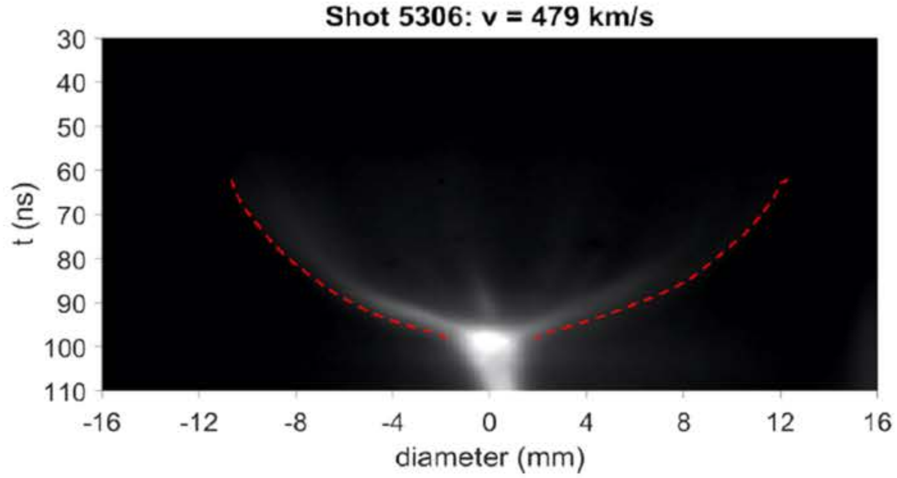
arpa·e CHANGING WHAT'S POSSIBLE

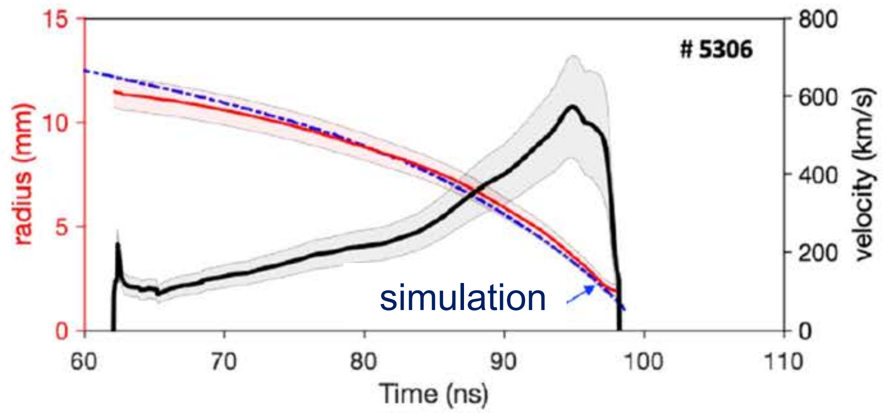
LBNL: P. Seidl et al., Rev. Sci. Instrum. **89**, 053302 (2018)
LANL/HyperJet: S. C. Hsu et al., IEEE Trans. Plasma Sci. **46**, 1951 (2018); Y. C. F. Thio et al., Fus. Sci. Tech. (2019).

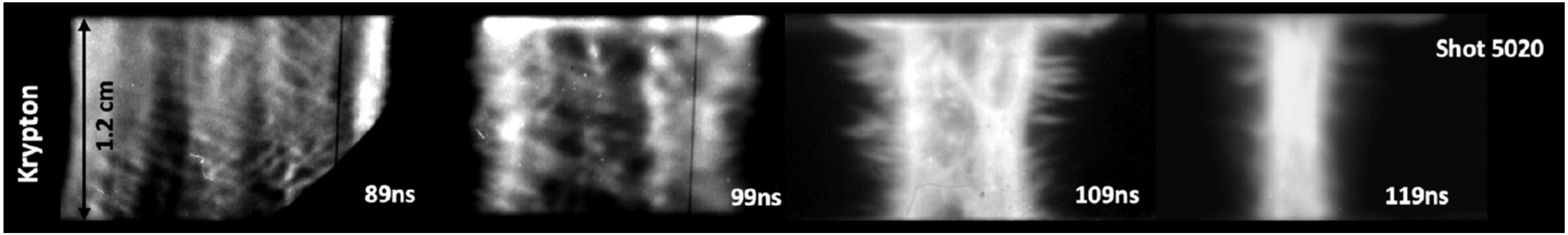
ALPHA concept: Stable staged-Z-pinch implosions at B_{Z0}>1.5 kG and DD neutron production on the 1-MA Nevada Terawatt Facility

Kr gas-puff liner gave the best results



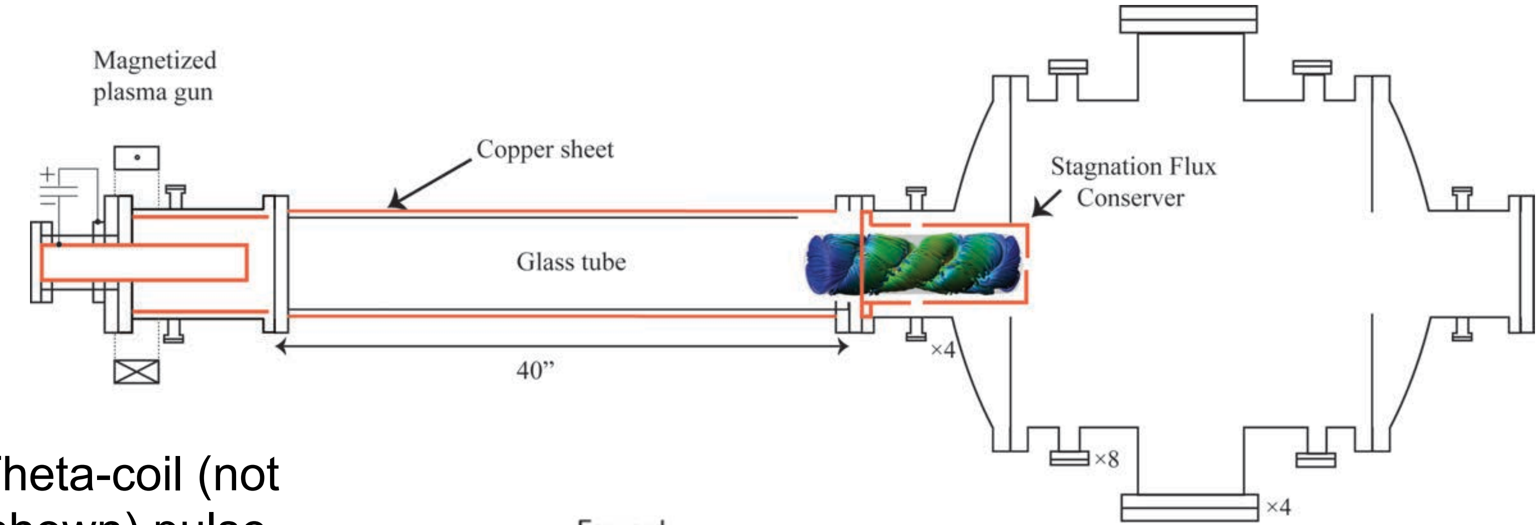




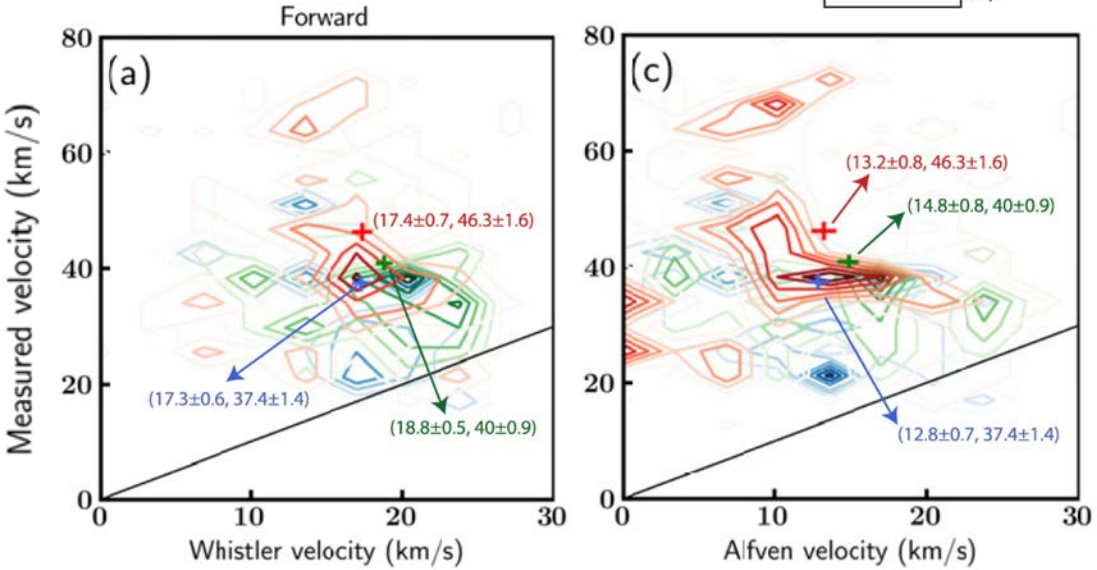


H. U. Rahman et al., Phys. Plasmas **26**, 052706 (2019).
J. Narkis et al., Phys,. Plasmas **26**, 032708 (2019).

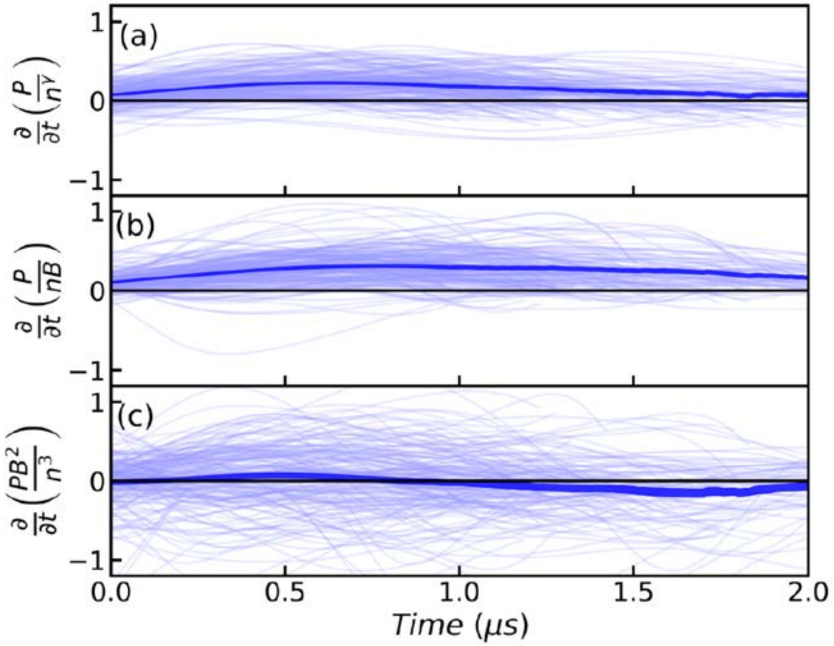
ALPHA applied science: Acceleration and compression studies of a helically relaxed Taylor state as a potential MIF target



Theta-coil (not shown) pulse generated super-thermal and super-Alfvenic waves rather than effective acceleration of the plasma



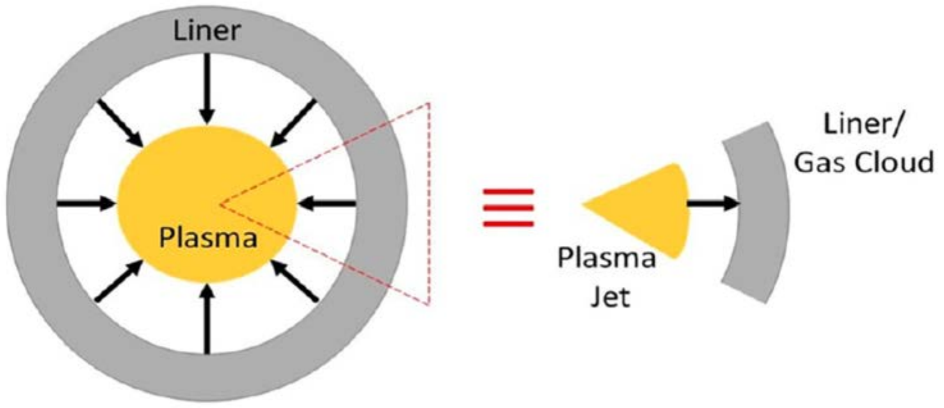
Equation of state during compression suggests better agreement with parallel CGL compared to MHD or perpendicular CGL

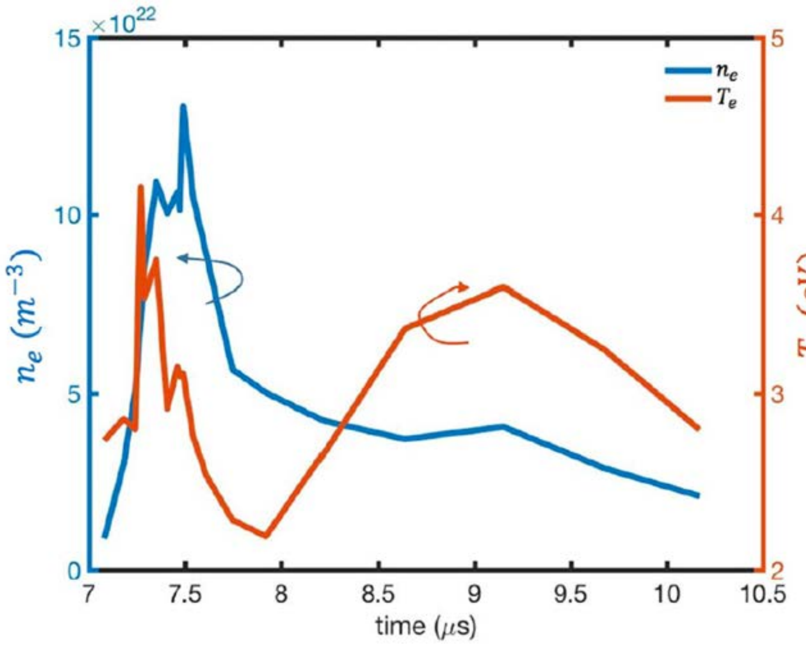


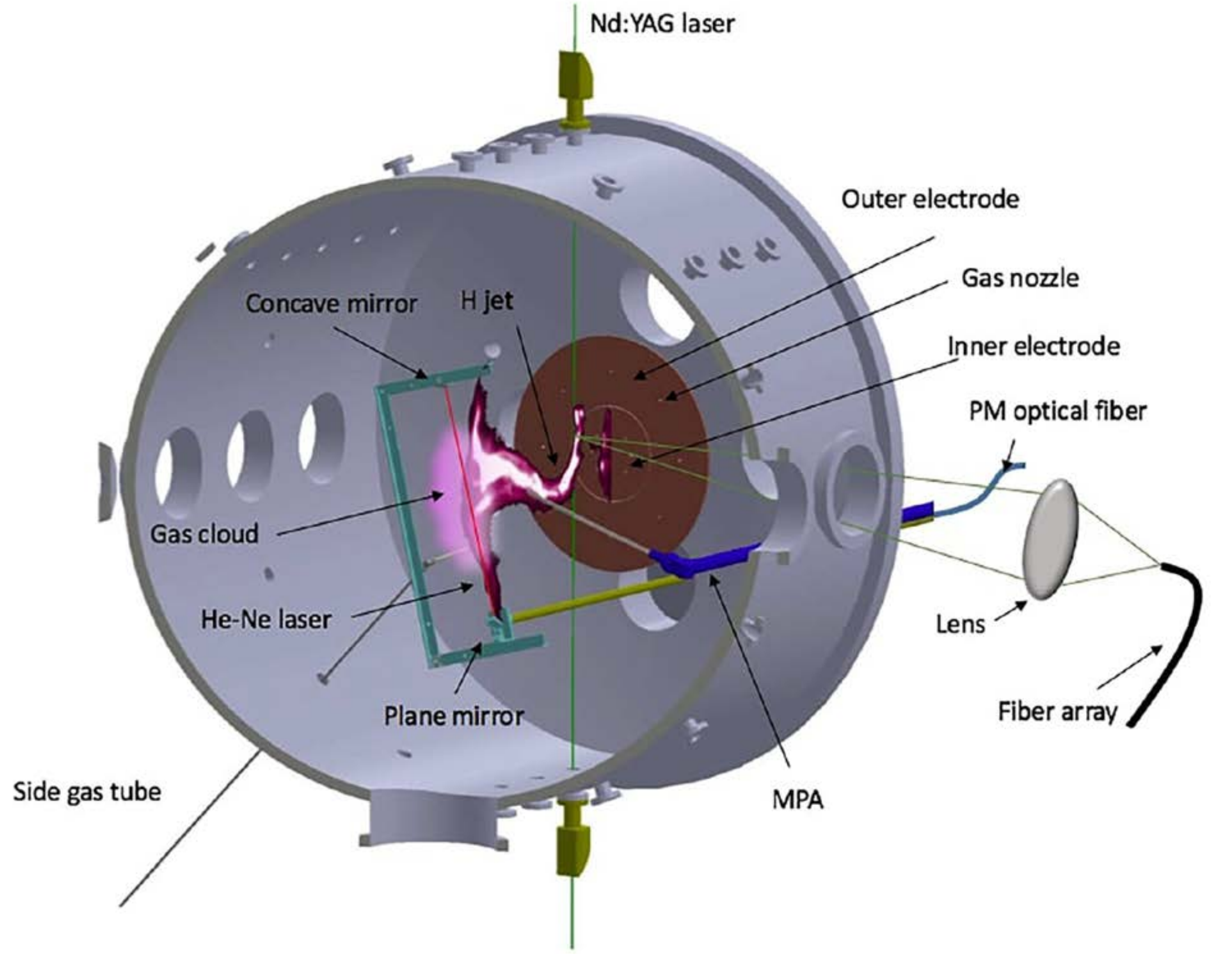
Ongoing work: merging of two Taylor-state plasmas to increase density

M. Kaur et al., Phys. Rev. E **97**, 011202(R) (2018)
M. Kaur et al., J. Plasma Phys. **84**, 905840614 (2018)

ALPHA applied science: Fundamental studies of plasma compression and heating



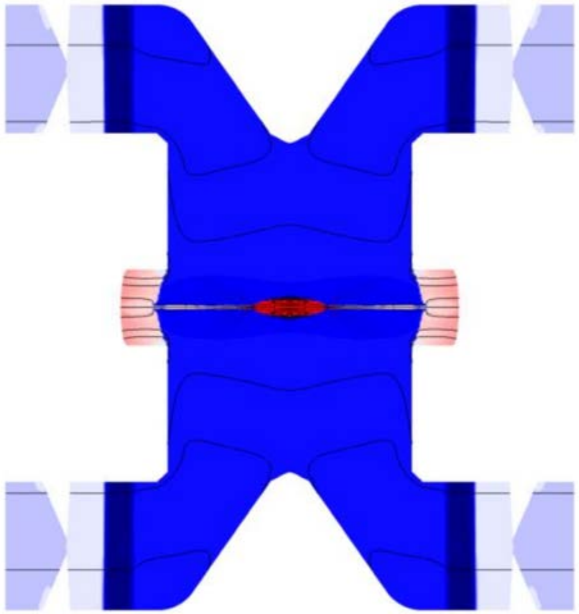




B. Seo and P. M. Bellan, Phys. Plasmas **25**, 112703 (2018)

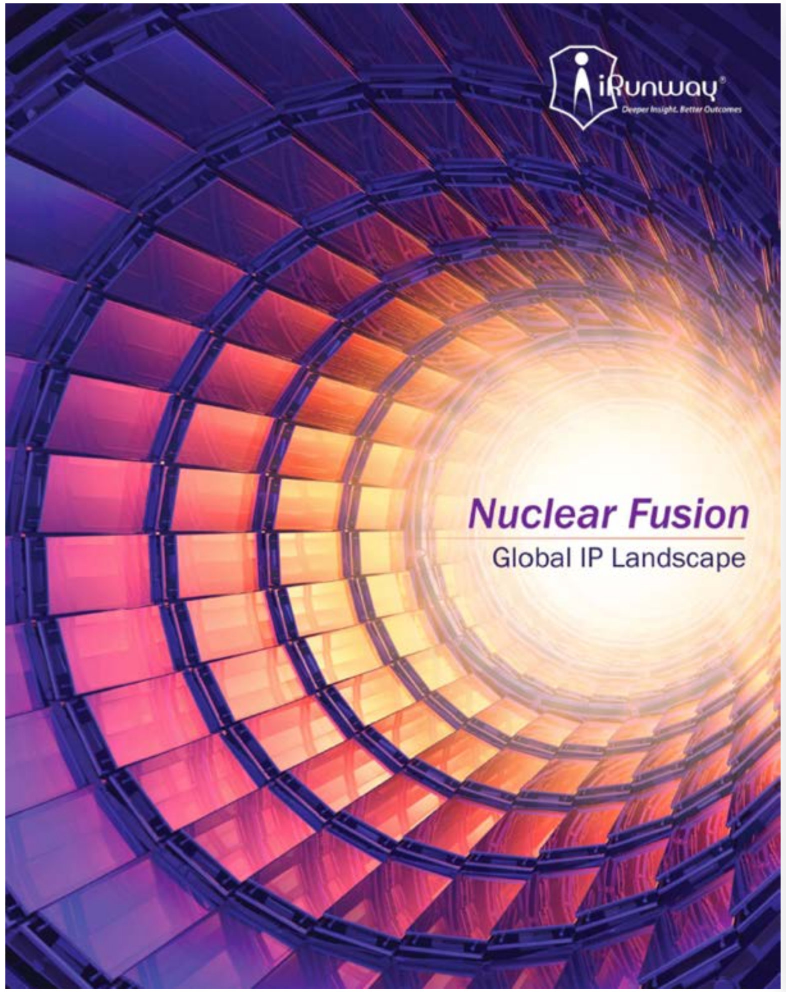
Other ALPHA projects (concept and driver)

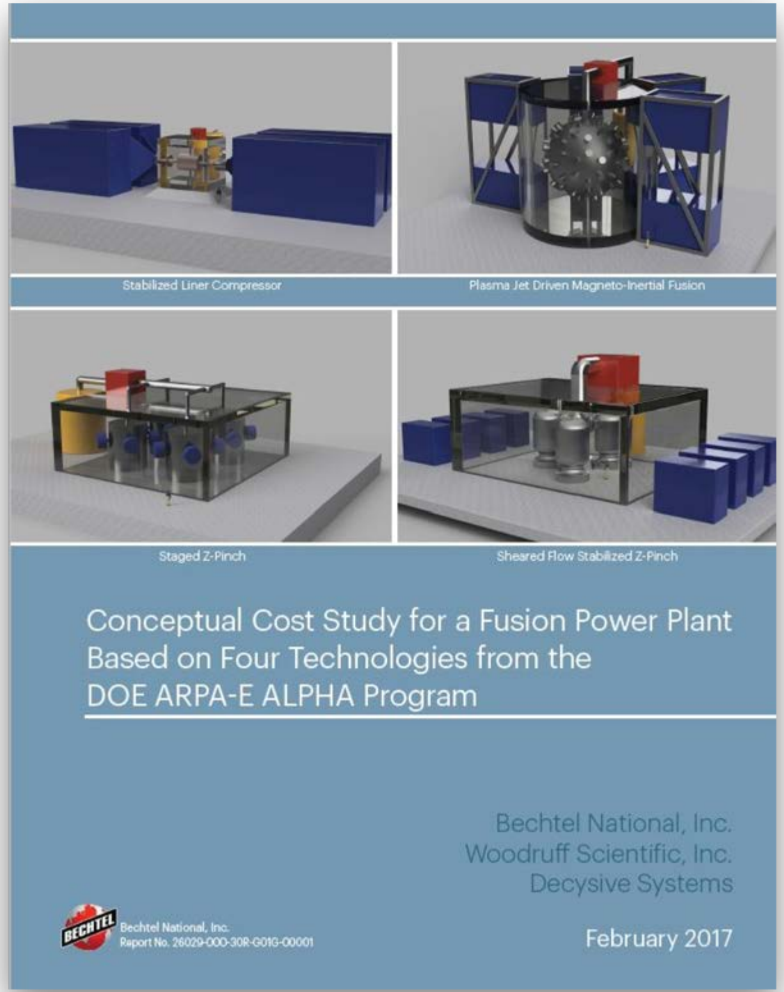
- Helion Energy: magnetic compression of FRCs formed by dynamic merging
  - Construction of “Fusion Engine Prototype” (FEP) device
  - Increased the magnitude of compression-magnetic-field strength and FRC flux
  - Advancing the plasma parameters of the compressed FRC
  - Generation and measurement of DD neutrons

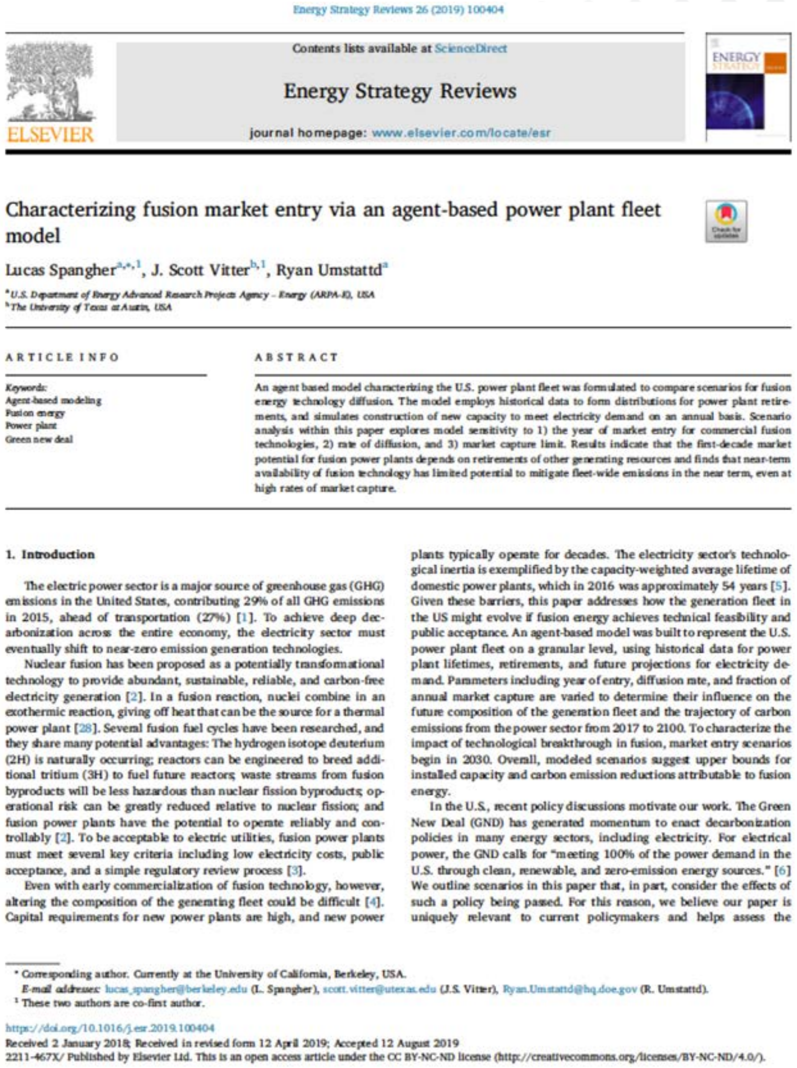


- NumerEx: Design of stabilized, rotating, imploding liquid liner
  - 1-km/s implosion speed using annular pistons
  - Developed engineering design of a system using NaK with 10-cm-diameter bore
  - Did not construct the system due to challenges with high-pressure valves and triggering

ALPHA's tech-2-market (T2M) component helped its teams with IP analysis, costing, and understanding fusion market entry







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ELSEVIER

Characterizing fusion market entry via an agent-based power plant fleet model

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ABSTRACT

An agent based model characterizing the U.S. power plant fleet was formulated to compare scenarios for fusion energy technology diffusion. The model employs historical data to form distributions for power plant retirements, and simulates construction of new capacity to meet electricity demand on an annual basis. Scenario analysis within this paper explores model sensitivity to 1) the year of market entry for commercial fusion technologies, 2) rate of diffusion, and 3) market capture limit. Results indicate that the first-decade market potential for fusion power plants depends on retirements of other generating resources and finds that near-term availability of fusion technology has limited potential to mitigate fleet-wide emissions in the near term, even at high rates of market capture.

1. Introduction

The electric power sector is a major source of greenhouse gas (GHG) emissions in the United States, contributing 29% of all GHG emissions in 2015, ahead of transportation (27%) [1]. To achieve deep decarbonization across the entire economy, the electricity sector must eventually shift to near-zero emission generation technologies.

Nuclear fusion has been proposed as a potentially transformational technology to provide abundant, sustainable, reliable, and carbon-free electricity generation [2]. In a fusion reaction, nuclei combine in an exothermic reaction, giving off heat that can be the source for a thermal power plant [28]. Several fusion fuel cycles have been researched, and they share many potential advantages: The hydrogen isotope deuterium (2H) is naturally occurring; reactors can be engineered to breed additional tritium (3H) to fuel future reactors; waste streams from fusion byproducts will be less hazardous than nuclear fission byproducts; operational risk can be greatly reduced relative to nuclear fission; and fusion power plants have the potential to operate reliably and controllably [2]. To be acceptable to electric utilities, fusion power plants must meet several key criteria including low electricity costs, public acceptance, and a simple regulatory review process [3].

Even with early commercialization of fusion technology, however, altering the composition of the generating fleet could be difficult [4]. Capital requirements for new power plants are high, and new power plants typically operate for decades. The electricity sector's technological inertia is exemplified by the capacity-weighted average lifetime of domestic power plants, which in 2016 was approximately 54 years [5]. Given these barriers, this paper addresses how the generation fleet in the US might evolve if fusion energy achieves technical feasibility and public acceptance. An agent-based model was built to represent the U.S. power plant fleet on a granular level, using historical data for power plant lifetimes, retirements, and future projections for electricity demand. Parameters including year of entry, diffusion rate, and fraction of annual market capture are varied to determine their influence on the future composition of the generation fleet and the trajectory of carbon emissions from the power sector from 2017 to 2100. To characterize the impact of technological breakthrough in fusion, market entry scenarios begin in 2030. Overall, modeled scenarios suggest upper bounds for installed capacity and carbon emission reductions attributable to fusion energy.

In the U.S., recent policy discussions motivate our work. The Green New Deal (GND) has generated momentum to enact decarbonization policies in many energy sectors, including electricity. For electrical power, the GND calls for "meeting 100% of the power demand in the U.S. through clean, renewable, and zero-emission energy sources." [6] We outline scenarios in this paper that, in part, consider the effects of such a policy being passed. For this reason, we believe our paper is uniquely relevant to current policymakers and helps assess the

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[1] These two authors are co-first author.

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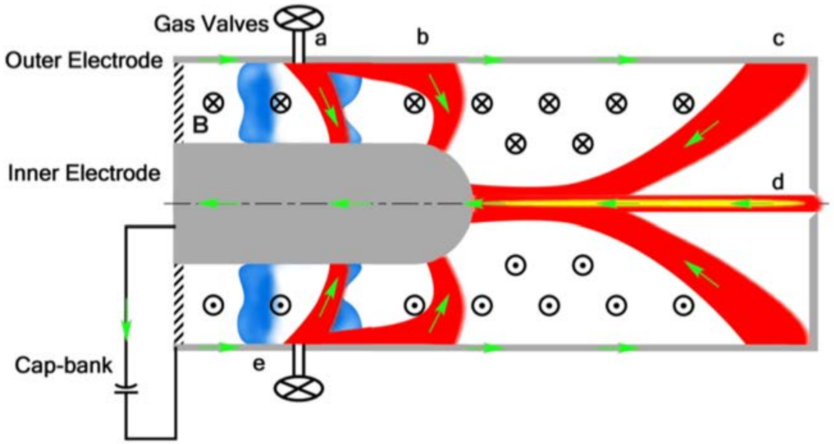
JASON summer study (2018) was commissioned by ARPA-E to review the ALPHA program

- Statement of work:
  - Assess progress of ALPHA and non-ALPHA MIF teams toward realizing low-cost fusion
  - Assess future needs to realize low-cost MIF
- Abbreviated findings:
  - MIF is physically plausible and rapid progress has been made despite having received ~1% funding of MCF and ICF; best performing system (MagLIF) is within a factor of 10 of scientific breakeven
  - Pursuit of MIF could lead to valuable spinoffs, e.g., fusion propulsion
  - MIF could absorb significantly more funding than ALPHA
- Main recommendations:
  - Investments to study plasma instabilities, transport, liner-fuel mix at MIF conditions
  - National Labs should contribute unclassified codes and user training
  - Develop components, e.g., plasma guns, pulsed power, diagnostics, advanced magnets, and materials
  - Near-term goal/priority should be scientific breakeven in a system that scales plausibly to a commercial power plant
  - Support all promising approaches as long as possible; do not concentrate resources on early frontrunners

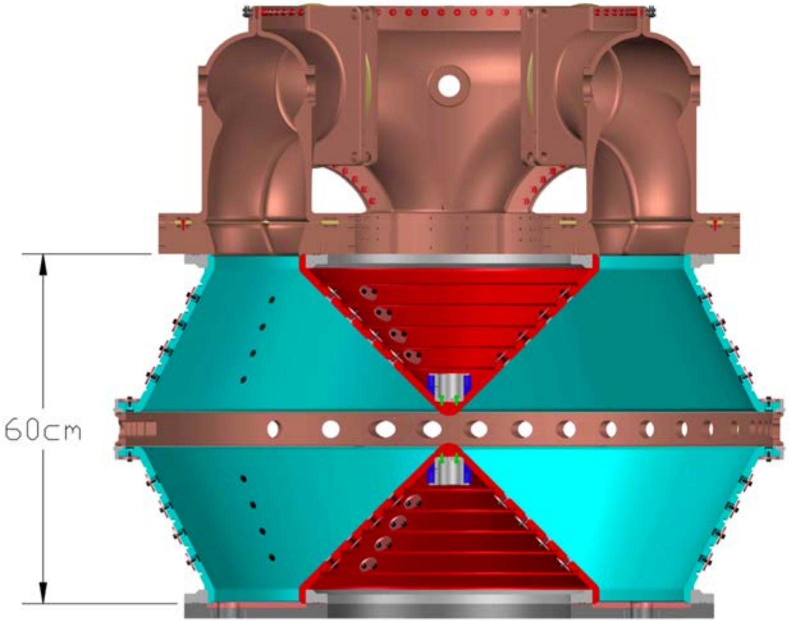
Full JASON report available to download.

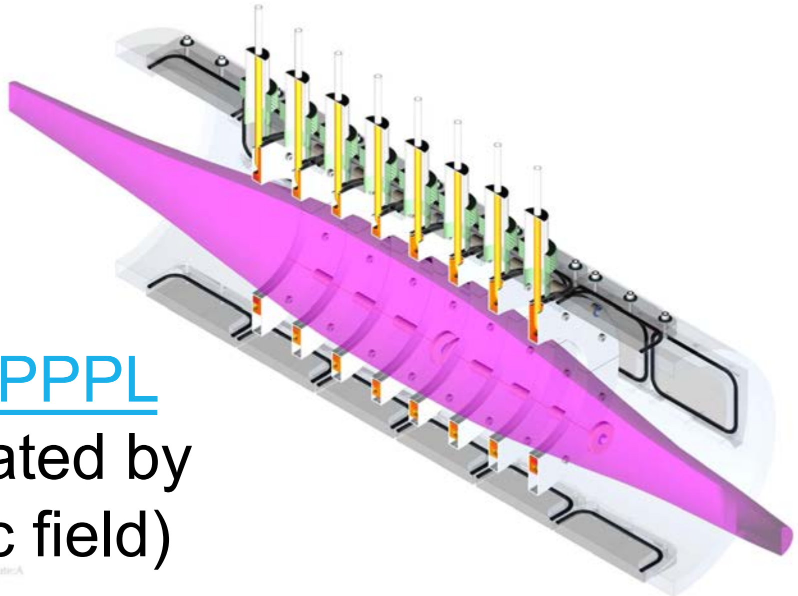
New fusion projects funded by ARPA-E OPEN 2018 program (represents expansion beyond MIF/Z-pinch-based concepts)

Zap Energy/UW ($6.8M, continuation of UW/LLNL ALPHA project)



CTFusion/UW ($3M, spheromak sustained by imposed dynamo current drive)





Princeton Fusion Systems/PPPL ($1.25M, FRC sustained/heated by odd-parity rotating magnetic field)

Diagnostic resource teams to support the validation of ARPA-E-supported fusion concepts ($7.3M, 2 yrs.)

Eight teams selected (July, 2019):

- ORNL, $1.1M, Thomson scattering (low density) and visible emission spectroscopy
- LLNL, $2M, Thomson scattering (high density)
- LLNL, $1.3M, neutron activation and nTOF detectors
- Univ. of Rochester/LLE, $1M, neutron activation and nTOF detectors
- UC, Davis, $444k, ultra-short-pulse reflectometry
- PPPL, $450k, passive charge-exchange ion energy analyzer
- LANL, $630k, filtered, time-resolved soft-x-ray imager
- Caltech, $400k, hard x-ray imaging, non-invasive B-field assessment

RFI on enabling technologies for a commercially viable fusion power plant

Recent ARPA-E Request for Information (RFI) on
Enabling Technologies for a Commercially Viable Fusion Power Plant

- Fusion market entry may require reduced nameplate capacity and capital cost compared to traditional fusion reactor cost studies (typically 1 GWe and >US$5B)
- Fusion power plants at reduced scale and cost likely will have different technology requirements
- Interest in:
  - Thick, liquid blankets (e.g., molten salts or liquid metals)
  - Corrosion-resistant, high-temperature materials
  - Smaller tritium-processing systems and minimum tritium inventory
  - Repetitive pulsed-power technology (for MIF, IFE approaches)
  - Specific challenges presented by use of advanced fuels
  - Compatibility with advanced power cycles
- Reduced emphasis on
  - Developing 150-dpa solid materials
  - Solid-material divertors

https://arpa-e.energy.gov